nature sustainability

Perspective

https://doi.org/10.1038/s41893-023-01194-6

Supplying ecosystem services on US rangelands

Received: 4 November 2022

Accepted: 5 July 2023

Published online: 04 September 2023

Check for updates

David D. Briske[1], Steven R. Archer[2], Emily Burchfield[3], William Burnidge[4], Justin D. Derner[5], Hannah Gosnell[6], Jerry Hatfield[7], Clare E. Kazanski[8], Mona Khalil[9], Tyler J. Lark[10], Pamela Nagler[11], Osvaldo Sala[12], Nathan F. Sayre[13] & Kimberly R. Stackhouse-Lawson[14]

Rangelands comprise 40% of the conterminous United States and they supply essential ecosystem services to society. A scenario assessment was conducted to determine how accelerating biophysical and societal drivers may modify their future availability. Four scenarios emerged: two may maintain rural communities by sustaining the prevailing ecosystem service of beef cattle production, and two may transform rural communities through expansion of renewable energy technologies and infusion of external capital from amenity land sales. Collaborative organizations representing diverse societal sectors may most effectively identify and manage trade-offs among ecosystem service availability, and equitably prioritize food and energy security, environmental quality and cultural identity.

Rangelands represent ecosystems that support native and naturalized vegetation, including grasslands, shrub-steppe, shrublands, woodlands and savannahs that are adaptively managed as social-ecological systems to benefit human well-being[1]. Rangelands comprise 40% of the conterminous US land area, primarily in the 17 western states, and are held in both public and private ownership[2]. These vast heterogeneous landscapes provide diverse ecosystem services—benefits that society receive from nature—that are categorized as provisioning, supporting, regulating and cultural[3]. Beef cattle production is currently the dominant provisioning service supporting the national and global demand for beef products. Accelerating changes in both biophysical and societal drivers are impacting both supply and demand for these services[4]. Here we use a 'scenario assessment' protocol to ascertain how these drivers may influence the supply of ecosystem services derived from rangelands throughout this century.

Scenario assessment provides a means to envision plausible futures under conditions of high uncertainty and low controllability over long planning horizons[5,6]. The process consists of a series of 'what if' questions that focus on critical concerns, system drivers and potential tipping points that may shape the future trajectory of social-ecological systems. Outcomes are primarily qualitative and expressed as a limited number of storylines designed to engage diverse stakeholders and inform science and policy. Scenario assessments typically involve four steps: (1) identification of a focal question(s), (2) determination of critical system drivers and uncertainties, (3) development of several plausible futures, and (4) analysis of potential implications and interventions to avoid, mitigate or promote specific scenarios[6].

The impetus for this scenario assessment emerged from a collaborative effort among 80 academics to publish an edited volume entitled

[1]Ecology and Conservation Biology, Texas A&M University, College Station, TX, USA. [2]School of Natural Resources and the Environment, University of Arizona, Tucson, AZ, USA. [3]Department of Environmental Science, Emory University, Atlanta, GA, USA. [4]The Nature Conservancy, Denver, CO, USA. [5]Rangeland Resources and Systems Research Unit, High Plains Grasslands Research Station, USDA-ARS, Cheyenne, WY, USA. [6]College of Earth, Ocean, and Atmospheric Sciences, Oregon State University, Corvallis, OR, USA. [7]National Laboratory for Agriculture and the Environment, USDA-ARS, Ames, IA, USA. [8]The Nature Conservancy, Minneapolis, MN, USA. [9]Ecosystems Mission Area, US Geological Survey, Reston, VA, USA. [10]Center for Sustainability and the Global Environment, Nelson Institute for Environmental Studies, University of Wisconsin-Madison, Madison, WI, USA. [11]Southwest Biological Science Center, US Geological Survey, Tucson, AZ, USA. [12]Global Drylands Center, School of Life Science and School of Sustainability, Arizona State University, Tempe, AZ, USA. [13]Department of Geography, University of California Berkeley, Berkeley, CA, USA. [14]AgNext, Colorado State University, Fort Collins, CO, USA. e-mail: dbriske@tamu.edu

Rangeland Systems: Processes, Management and Challenges[1]. The critical contribution of ecosystem services provided by rangelands and the ability to maintain their supply to meet future demands emerged as central themes of that volume. Two change drivers anticipated to have the greatest impact on the supply of rangeland ecosystem services were: (1) the biophysical consequences of climate change and increasing climate variability, and (2) societal priorities shifting from provisioning towards cultural ecosystem services. These drivers represent the foundation on which 14 academic, agency and non-governmental scientists, with diverse disciplinary expertise and extensive knowledge of US rangelands, developed this scenario assessment.

The focal question for this scenario assessment is 'how will biophysical and societal changes modify the supply of key ecosystem services from US rangelands throughout the twenty-first century?'. These scenarios, either independently or in combination, will impact food and energy security, environmental quality, cultural identity and livelihoods. Consequently, greater awareness of plausible scenario trajectories, and associated trade-offs and tipping points among various categories of rangeland ecosystem services is required to proactively develop adaptation and mitigation strategies and identify potential opportunities. Although our assessment is focused on the United States, these change drivers, scenarios and implications are relevant to global rangelands and food security.

Primary change drivers

The dominant biophysical and societal drivers anticipated to have greatest impact on the supply of rangeland ecosystem services throughout the century are summarized below.

Dominant biophysical driver

Atmospheric warming in the United States is projected to increase by 1.4 °C and 1.6–4.1 °C by the mid- and late twenty-first century, respectively[7]. Precipitation will increase in the northern region, but decrease in the southern and southwestern regions. The West will become more arid and the East will become less arid with a crossover point at approximately 100° N longitude[8]. A trend of increasing aridity throughout the West is substantiated by decreasing rates of evapotranspiration since 2000 (ref. 9) (Fig. 1). Precipitation variability in the West is projected to continue to increase along with the frequency and magnitude of extreme climate events, especially droughts and deluges[8]. Notably, greater frequency and duration of severe, multiyear droughts are predicted for the Southern Great Plains and the Southwest[10].

Climate change has adversely impacted biodiversity, wildlife habitat and other critical ecosystem services throughout the West, especially in riparian corridors[11]. Climate change will adversely impact livestock grazing, a primary rangeland use, via effects on forage quality and quantity, ectoparasite abundance and thermal stress on animals[12]. Climate warming will further decrease snowpack extent and persistence, stream flows, and water storage in lakes and reservoirs, which will exacerbate current water shortages primarily in summer when both environmental and anthropogenic demands are highest[7]. The frequency, intensity and extent of forest[13] and rangeland wildfires will continue to increase in the West[14]. Climate-induced expansion of non-native annual grasses throughout the West will provide fine fuel loads to further increase rangeland wildfires that suppress fire-sensitive native species[15].

Dominant societal driver

Societal demand for rangeland ecosystem services has been shifting from provisioning (for example, forage and beef cattle production) to cultural and amenity services (for example, recreation, ecotourism, suburban and exurban development, and hobby ranching) in recent decades[2,4]. This is a consequence of both demographic growth and migration[16,17]. Initially defined as a willingness of new ranch owners to exchange lifestyle benefits for marginal economic returns[18], amenity services have expanded to reflect a widespread prioritization of recreation, exurban residential development, and conservation and speculative investment. More recently, the potential value of regulating (for example, soil carbon sequestration) and supporting services (for example, biodiversity and natural resource conservation) have gained increasing recognition, for example, the Ecosystem Services Market Consortium (https://ecosystemservicesmarket.org).

Declining profitability of rangeland livestock production has produced a large and growing 'rent gap'—the difference between current and potential income—especially in peri-urban and high-amenity areas. The median income of livestock-producing households in the United States in 2020 was negative (https://www.ers.usda.gov/topics/farm-economy/farm-household-well-being/farm-household-income-estimates/). However, the market value of ranch properties continues to rise, far exceeding the net present value of revenue generated by livestock production[19]. These trends gained momentum in the 1990s. For example, approximately 40% of all ranch sales in 10 counties in the Greater Yellowstone Ecosystem between 1990 and 2001 were to amenity buyers[18]. Current trends in landownership and land concentration may combine to create vast private estates in regions of high conservation and amenity value[20]. The concentration of landownership also represents a concentration of power within an increasingly small, elite group to dictate land use and ultimately conservation futures[21].

Development of plausible futures

Our collective assessment of the two critical system drivers generated four plausible future scenarios: (1) grass-finished beef, (2) modern pastoralism, (3) diversified ecosystem services and (4) amenity ranching (Fig. 2). These scenarios, which emerged from a series of informal email and virtual meetings among the authors, depict the potential consequences of biophysical and societal changes and their interactions, on both the magnitude and categories of ecosystem services supplied by US rangelands. We recognize that these scenarios may be expressed in various combinations in response to the heterogeneous manifestation of both the biophysical and social drivers, and that their consequences may vary temporally among social-ecological regions. However, here they are presented independently for brevity and clarity.

Grass-finished beef scenario

The predominant practice of grain-finished beef production will become unsustainable as climate change substantially reduces crop yields and increases grain prices, resulting in intensified competition between food and feed for limited water and land resources. Environmental quality, animal welfare and antimicrobial resistance will continue to challenge the viability of grain-finished beef cattle production[22]. However, a high demand and market value for locally sourced beef, and the vital importance of rangeland beef production to human food security will support economically viable and ecologically sustainable grass-finished beef production.

Beef cattle production is financially the largest agricultural sector in the United States with receipts of US$63.1 billion, and it is the dominant rangeland provisioning service supplying 93.8 million cattle, 40.7 million beef cows and 12.3 million tons of beef in 2020 (https://www.ers.usda.gov/topics/animal-products/cattle-beef/statistics-information/). Approximately 60% of the United States cow herd occurs on rangelands in 10 states, 8 of which are in the Great Plains where the vast majority of land is privately owned (https://quickstats.nass.usda.gov/results/6ED88A30-0BCC-37D0-A6D3-5B0BE7A680CD). Rangeland beef production is critical to food security because it converts high cellulose plant biomass, which is inedible to humans, into a highly desirable, protein-rich food source[23].

The vast majority (95%) of beef cattle in the United States are currently finished on corn and corn by-products in confined feeding facilities before harvest to increase the efficiency, consistency and quality

https://doi.org/10.1038/s41893-023-01194-6

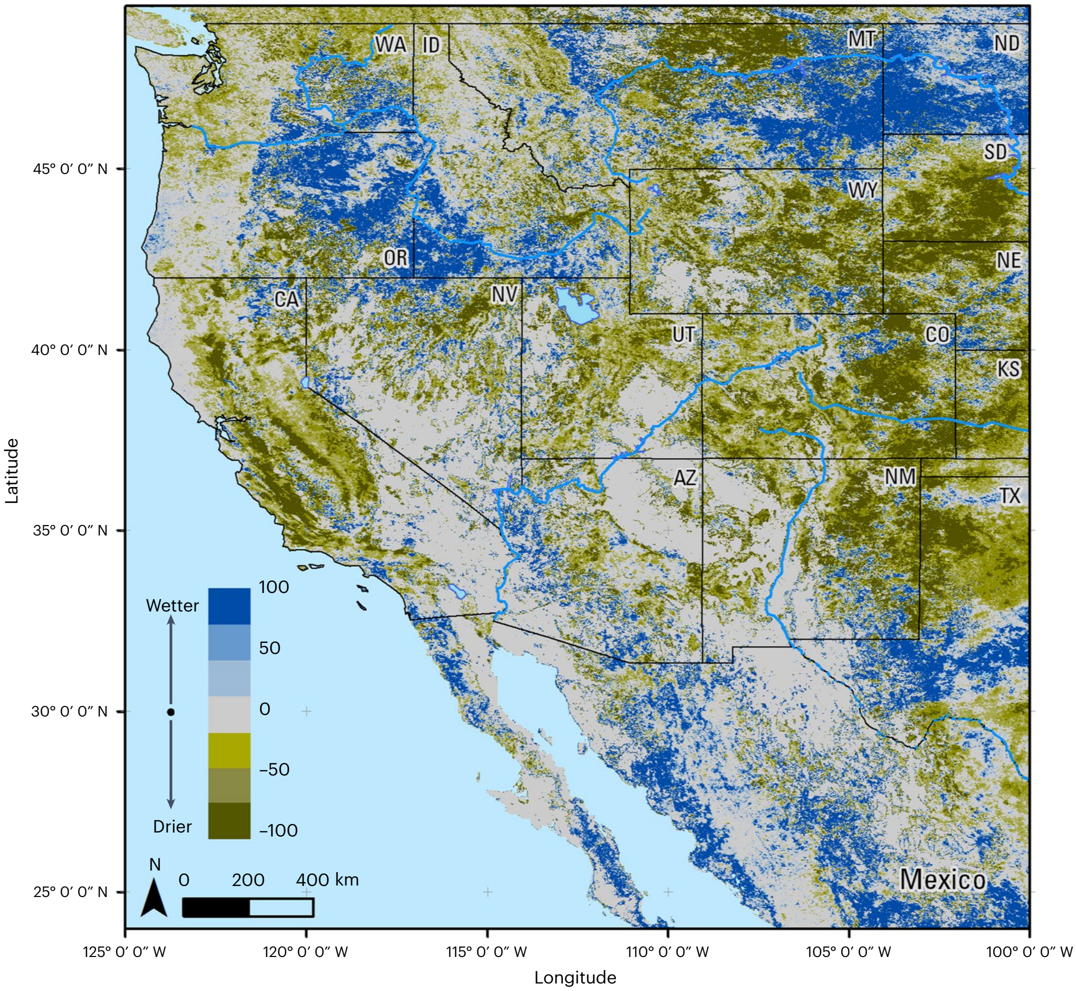


Fig. 1 | Change in evapotranspiration in the western United States. Relative change (%) of seasonal (April and May; mm) evapotranspiration anomalies between 2000 and 2020 illustrates a trend of increasing aridity in the western United States. Evapotranspiration anomalies for both years are expressed as a percentage of total seasonal evapotranspiration compared with the mean seasonal evapotranspiration for 2001–2015 (ref. 9). Data from the US Geological Survey (https://earlywarning.usgs.gov/ssebop/modis/8-day).

of beef production[24]. Use of concentrated feeds with greater digestibility than rangeland forage has reduced methane emissions, and, in combination with improved animal breeding, has accelerated animal growth rates to shorten the time from birth to harvest. This increase in production efficiency has reduced both the land area required and greenhouse gas (GHG) emissions per kilogram of beef[25,26].

Corn yields are projected to decrease >50% in the Corn Belt by 2050 in response to increasing maximum July and minimum August temperatures, coupled with more variable rainfall[27]. Yield decreases are anticipated to initially occur in the southern region of the Corn Belt where it will adversely impact the economic viability of corn production[28]. A substantial decrease in corn production and an associated increase in its market price may reduce the economic viability of corn-finished beef production. Corn may potentially be replaced by other crops, including wheat, barley and grain sorghum, that are more climatically suited to the region[27]. These grain crops may provide alternative sources of cattle feed and they can be grown with fewer agricultural inputs than corn.

A shift from grain- to grass-finished beef does not completely mitigate the ecological footprint of beef production because the majority (70%) of resource use and GHG emissions occur in the cow-calf phase on grazing lands, including rangelands and other forage production systems[29]. GHG emissions, primarily as methane, are estimated to be 40% higher per kilogram of beef and 8% higher per unit land area for grass- than grain-finished beef[30]. Conservative stocking rates can lower enteric methane emissions by allowing cattle to select higher-quality diets, but high forage quality is not available on semiarid rangelands throughout the year[31]. Interventions such as diet reformulation, feed additives and animal breeding are being investigated to reduce enteric methane emission in cattle[32]. However, their potential for commercial application, economic implications for beef producers and consumer acceptance have yet to be determined.

Grass-finished beef production has been estimated to yield only 27–50% of grain-finished beef production, because of a reduction in production efficiency associated with lower feed quality and extended time from birth to harvest[23,24]. However, environmental benefits would emerge from a decrease in the use of corn as a cattle feed, including less fertilizer use and eutrophication[33], reduced water use for irrigation[34] and less soil erosion in the US Corn Belt[35]. Grass-finished beef production could increase carbon sequestration through restoration of marginal cropland to perennial grasslands[36,37] and reduce rangeland conversion to cropland, which contributes to the loss of soil carbon and biodiversity, including valuable wildlife habitat[38,39]. In addition, it would provide alternative options for the use of arable lands currently in corn production[23].

The large ecological footprint of beef production has increased societal pressures to use and verify implementation of sustainable production practices[40]. Numerous multinational food companies have

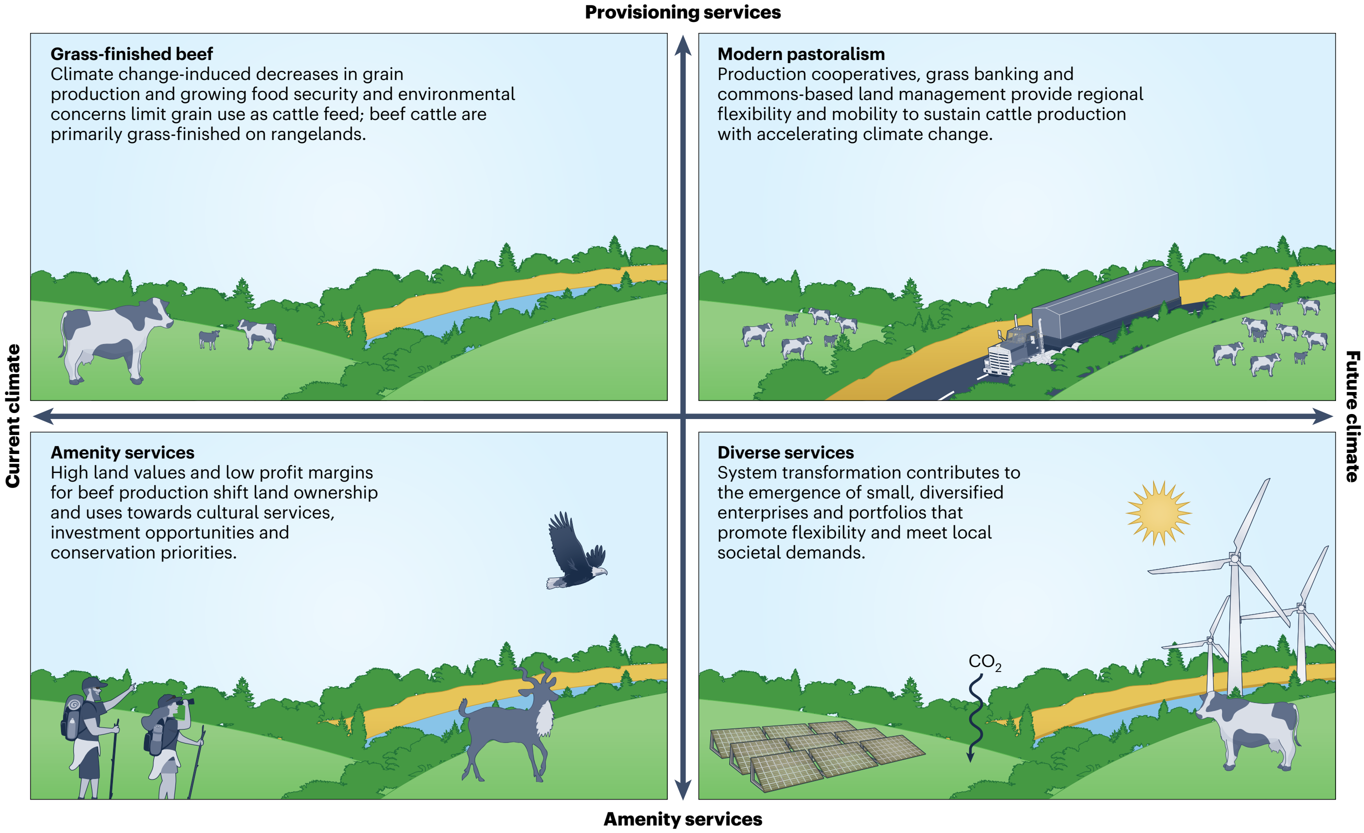


Fig. 2 | Plausible future scenarios for US rangeland. Four scenarios depicting how climate change and a societal shift towards cultural (amenity) ecosystem services may modify the supply of ecosystem services from US rangelands in the twenty-first century.

implemented sustainability programmes, including net-zero commitments inclusive of their supply chains, including upstream to the ranching community. Imposition of top-down sustainability requirements made without beef producer input and financial commitments to support these initiatives may further threaten the economic viability of beef producers and their local communities.

This scenario represents a return to extensive beef cattle production—a priority provisioning service—and a potential increase in both supporting and regulating ecosystem services by conserving and restoring rangelands. However, it would result in a large reduction in both the efficiency and the amount of beef production. Societal acceptance of higher beef costs and the willingness to consume less beef or shift dietary preferences to alternative meat products will be a major consideration[22,37]. Reduced beef production and higher beef prices in the United States, in the absence of a corresponding decrease in demand, may contribute to the expansion of beef production in developing countries that would exacerbate biodiversity loss and increase global GHG emissions[41].

Modern pastoralism scenario

Conventional adaptation strategies and enterprise diversification at the ranch scale will prove to be insufficient to maintain economically viable beef cattle production with climate change and variability; however, novel regional-scale adaptive strategies will emerge through innovations in management and governance that resemble traits associated with nomadic pastoralism—flexibility, mobility and reciprocity[42].

The adaptive capacity of many beef producers—their ability to recognize, respond and manage system change—is currently insufficient to contend with climate variability at the scale of individual ranches[43,44]. Inaction is a common response to drought and climate variability for a variety of reasons, including advanced landowner age, insufficient financial resources and inadequate technical knowledge. Beef producers place great value on their judgement and experience, and many consider their peers an important source of information regarding ranch management[44]. However, this may prove insufficient or even maladaptive when confronted with climate variability beyond their collective experience (Fig. 1). Consequently, projected climate change and variability may exceed the adaptive capacity needed to ensure economic viability and ecological sustainability[12]. Adaptation strategies are specifically needed to minimize the devastating economic impacts of destocking–restocking cycles and to minimize the potential for rangeland overgrazing associated with periods of economic hardship.

The goal of modern pastoralism is to sustain beef cattle production by opportunistically matching variable rangeland forage production to livestock demands across regional landscapes. This strategy buffers local communities of beef producers and consumers from exogenous change drivers through institutional innovations, including production cooperatives, and more collective or 'commons based' land-management systems. The resulting 'collective benefits'—benefits that individual ranchers cannot obtain—are likely to increase as climate variability further challenges the sustainability of rangeland beef production[42]. For example, Australians use 'agistment' to match the spatial scale of rainfall and forage production with that of livestock distribution[45]. This process is based on agreements among ranchers whose forage production differs widely in specific years owing to the high degree of spatial variation of precipitation. Large-scale cattle transport in California underscores the feasibility of this scenario[46]. Approximately 50% of the state's calf crop (500,000 animals) is annually relocated to grazing lands and feed yards out of state within a 12-week period.

Spatial limitations of individual ranch size impose an additional constraint on adaptive capacity for most beef producers. Greater land access and cattle mobility can be achieved through consolidation of properties[20,21] or development of regional cooperatives to enhance economies of scale. This will require that the place-based knowledge and management capacities of multiple producers be coordinated across existing property boundaries at regional scales. Innovative mid-term weather forecasts and forage projections, improved beef cattle inventories and market projections, coupled with increased efficiencies in information sharing and transportation logistics, would provide the integration needed throughout the beef supply chain for the transition to modern pastoralism.

Provisioning services of forage and beef production remain a high priority in this scenario, but with greater management complexity and costs necessitated by increasing climate variability. Projections for increasing climate warming and variability, coupled with the limited adaptive capacity of many beef cattle producers, suggest that transformational adaptation may be required to sustain economically viable rangeland beef production. Transformational adaptation may focus on comprehensive, regional adaptation planning led by coalitions of local-to-regional-scale private actors and groups, with support from the beef industry and state and national agencies[47]. Management plans and policies for state and public land-grazing leases will need to engender flexibility and coordination across landownership and jurisdictional boundaries. The Outcome-based Grazing Authorization programme initiated by the Bureau of Land Management to develop more effective grazing regulations through enhanced collaborative management with its partners is an example of this trend (https://www.partnersinthesage.com/outcome-based-grazing).

Diversified ecosystem services scenario

Transformation of social-ecological systems in response to the combined impact of climate and societal drivers will result in the emergence of diversified enterprises that develop and capitalize on climate change mitigation, renewable energy production, niche markets and other emerging opportunities on rangelands. The diverse portfolio of ecosystem services provided by these varied enterprises will emerge as an adaptive response to future change and accommodate local societal demands and priorities.

The prevailing industrial agricultural model has traditionally focused on optimal, cost-effective production of select provisioning services and economies of scale. The interactions between climate change and variability, and shifting societal demands are anticipated to disrupt the industrial model and incentivize production of alternative ecosystem services. Arable lands that no longer support economically viable crop production will become suitable for multiple competing uses, including grass-finished beef production, natural climate solutions to sequester soil carbon, renewable energy generation, amenity services and biodiversity conservation.

The vast area of US rangelands contains a large soil carbon pool that is vital to climate change mitigation. This has stimulated interest in 'carbon ranching' where landowners are compensated for additional carbon sequestration resulting from modified land management via established carbon markets[36,48]. Voluntary markets for soil carbon sequestration-based credits or offsets for GHG emissions are in various stages of development for croplands as well as rangelands, for example, Climate Action Reserve (https://www.climateactionreserve.org/how/protocols/ncs/grassland/). However, they have previously met with limited success because of substantial challenges on both the demand and the supply sides[49]. Consequently, the future success of voluntary agricultural carbon markets in the US remains uncertain, but they may be influenced by emerging governmental programmes to support climate-smart commodities (https://www.usda.gov/climate-solutions/climate-smart-commodities).

Optimism regarding 'carbon ranching' has been tempered based on unrealistic experimental assessments, biased sampling procedures and limited recognition of climate change impacts on future carbon sequestration potential[48]. The ability of grazing management to modify soil carbon is highly context specific because rangelands span multiple biomes and climates, various natural disturbance regimes and legacies of diverse land-use practices[36]. A global meta-analysis of arid and semiarid rangelands found that low grazing intensities were associated with small increases in soil carbon, whereas high grazing intensities were associated with small decreases[50].

This suggests that the most effective contribution of rangelands to climate change mitigation may be achieved by conservation of existing soil carbon pools, and restoration of depleted soil carbon pools in marginal croplands following conversion to perennial grasslands[36]. Woody plant encroachment has a much greater potential to increase soil carbon than does grazing management in semiarid and sub-humid regions, but it may decrease soil carbon in arid regions[51]. However, woody plant encroachment involves substantial trade-offs with other ecosystem services supplied by grasslands (for example, forage and cattle production, hydrology and biodiversity) that may negate any potential benefits of increased carbon sequestration[52].

Rangelands are well suited for wind and solar energy generation, and they can effectively accommodate the large land footprint and limited water requirements of these technologies[53]. Crude oil production is anticipated to plateau in the Southwest, Great Plains and Rocky Mountain regions by 2050, while energy derived from wind and solar sources are projected to double between 2020 and 2050 (https://www.nrel.gov/docs/fy20osti/75284.pdf). The expansion of renewable energy is driven by societal demand for low-carbon electricity, government incentives, cost competitiveness with natural gas and coal, and minimal water requirements[54].

Existing wind facilities are concentrated in the Great Plains region (https://www.eia.gov/energyexplained/wind/where-wind-power-is-harnessed.php), whereas solar facilities are more widely distributed (https://www.eia.gov/energyexplained/solar/where-solar-is-found.php). The direct land area per megawatt of electricity produced by an industrial wind turbine is smaller than for solar photovoltaic farms, but the larger, contemporary wind turbines require greater spacing which has reduced their capacity density (MW ha^{-1})[55]. Utility-scale solar farms vary considerably in size (1–500+ MW capacity) and distribution, but rangelands of southern Great Plains and far-western regions have large concentrations (https://www.nrel.gov/docs/fy20osti/75284.pdf).

Renewable energy technologies are a source of low-carbon power that may reduce reliance on fossil fuel-based technologies that emit GHGs. However, renewable energy technologies also have substantial environmental and societal downsides. Wind and solar energy generation has a large land footprint per megawatt of electricity compared with non-renewable energy, although this may be partially mitigated by multiple land-use opportunities and strategic siting[53,55]. For example, agrivoltaics may benefit the food–energy–water nexus by co-locating solar panels and agriculture to improve microclimatic conditions and increase delivery of ecosystem services[56]. However, the negative impacts of land conversion, fragmentation and infrastructure development may adversely affect terrestrial and avian wildlife movement, behaviour and persistence[57].

This scenario represents a major transformation in the categories of ecosystem services supplied by rangelands in response to climate change and the pressing need to reduce GHG emissions. Rangeland livelihoods will be derived from a varied portfolio of ecosystem services supplied by diversified enterprises that provide sufficient flexibility to accommodate subsequent socioeconomic changes. However, the potential for economically viable carbon markets and cost-effective wind and solar energy generation may dominate this scenario because of increasing societal demand for climate change mitigation. Cost-effective advances in renewable energy technologies that increase energy generation per unit land area may incentivize landowners to diversify income streams and invigorate rural economies.

 https://doi.org/10.1038/s41893-023-01194-6

Amenity ranching scenario

Increasing land values and low profit margins for beef cattle producers will continue to shift rangeland use and ownership from family-owned ranches towards individuals and non-ranch corporations with sufficient financial capital to prioritize amenity services and long-term asset appreciation. Cultural ecosystem services, including recreation, ecotourism, hobby ranching and native habitat restoration, will grow in importance, reflecting shifting societal values and new owners seeking to reconnect to the land.

The gap between agricultural incomes and amenity land values continues to widen and further incentivize shifts in landownership and use[20]. Low profit margins, the high median age of beef producers and decreasing intergenerational transfer within family ranches will continue to promote land sales[19,43]. A portion of these acquisitions will be driven by speculation and result in consolidation with existing ranches; others will be associated with amenity buyers, especially in regions with high aesthetic and cultural values[18]. This will accelerate the shift from land use focused on provisioning services to more multifunctional rural lands, a trend that has been occurring for the past several decades in developed countries[16].

Increasing amenity landownership will introduce both potential benefits and challenges for rural communities. Conservation priorities shared by local ranchers and amenity owners may create collaborative partnerships that effectively address emergent challenges posed by accelerating biophysical and socioeconomic drivers[17]. Although, specific motivations among amenity owners may vary widely[18], potential opportunities for enhanced rangeland sustainably include adoption of novel management and restoration programmes, improved property caretaking and creative leasing arrangements, with opportunities for local employment and philanthropic investment in local communities[16].

The challenges associated with amenity ownership vary widely and some may be highly consequential. Increased land and real-estate values may financially disadvantage local landowners and exclude ownership by new, less wealthy individuals[16,17]. Livestock-related agribusinesses (for example, farm and feed stores, and veterinarians) may be adversely impacted, depending on the extent to which amenity owners continue cattle production, with implications for local job markets and community organizations (for example, medical facilities, churches and schools). Amenity owners often lease land to local ranchers to continue livestock production, which secures an agricultural tax exemption for the amenity owner, even as their primary economic motivation lies in other services or asset appreciation[19]. Local community dynamics may be disrupted because amenity owners often have limited appreciation for the ranching culture, weak ties to local communities, and increase the potential for rapid property turnover. Conservation outcomes may be compromised by well-intended, but ill-advised activities that contribute to habitat fragmentation, introduction of exotic species, expanded coverage of invasive plants and dewatering of streams[17,18].

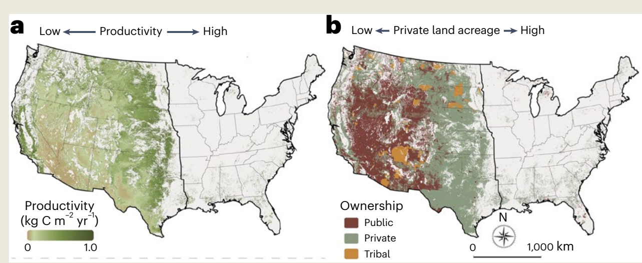
An accelerating demand for amenity services may create consequential changes in land use, governance, infrastructure and the dynamics of rural communities, including the potential for socioeconomic inequality and exploitation[17]. In regions with high amenity value, multigenerational family ranches may be displaced, and properties may be purchased by amenity buyers to create conservation estates[20]. Amenity uses of private rangelands may affect adjacent public rangelands by reducing demand for grazing leases and federal land revenues, creating opportunities to provide alternative ecosystem services, and modifying political support for federal land management agencies[58] (Box 1). The continued decline of infrastructure, markets and human relationships and lifestyles within ranching communities may accelerate the transition to a 'New West' characterized by a service-based, amenity-oriented economy[17,19].

BOX 1

Rangeland governance in the western United States

Rangeland governance is especially complex in the western United States because it involves diverse landownership, including private, federal, state, tribal, municipal and non-governmental organizations[17]. Consequently, management and governance are challenged by varied statutory and jurisdictional mandates, stakeholder interests and management objectives. These landownership patterns are further complicated by unique ecological attributes that influence the supply of ecosystem services.

- Private rangelands often occur at lower elevations, have greater access to surface water and have twice the forage production compared with public rangelands[63]. However, distinct landownership does not preclude the occurrence of critical ecological and socioeconomic interactions among private and public lands.
- Many ranches in the western United States are dependent on public rangelands, made available via long-term leases, as an important source of summer forage on high-elevation rangelands[19].
- Greater restrictions on livestock grazing on public lands, with the intent of increasing alternative categories of ecosystem services to achieve 'multiple use' mandates, may create unintended consequences for the sustainable supply of ecosystem services on private lands[64]. For example, the loss of summer grazing on public land may reduce herd size, intensify rangeland use and incentivize land conversion to forage crops or exurban development on nearby private lands.
- The capacity to anticipate and manage adverse outcomes of social-ecological systems involving multiple landownership and jurisdictions will require greater development of hybrid governance systems. Collaborative adaptive management and community-based conservation are two relatively recent trends in rangeland governance that have emerged as a means to resolve tensions between more centralized (federal) and decentralized (local private) forms of governance[17,58].



Complex rangeland ownership and governance. **a**,**b**, Spatial distribution of annual biomass production (**a**) and private, public and tribal landownership in the western United States (**b**). Figure reproduced with permission from ref. 63, Wiley.

Scenario implications

Our scenario assessment highlights the diversity and importance of ecosystem services supplied by US rangelands and the potential trajectories of their future delivery. The grass-finished beef and modern pastoralism scenarios emphasize the conventional provisioning services of forage and beef production, but with highly modified production strategies necessitated by increasing climate change and variability. The diversified ecosystem services scenario expands the portfolio of provisioning, and potentially regulating and supporting, services with greatest priority on soil carbon sequestration and renewable energy generation. The amenity ranching scenario describes an increasing transition from provisioning to cultural services in response to an accelerating increase in amenity land values relative to agricultural revenues.

The spatial and temporal expression of these four scenarios will vary among rangeland regions in response to the heterogeneity of both biophysical and social drivers. For example, the grass-finished beef and modern pastoralism scenarios may be more prevalent in the Great Plains region where extensive forage resources support 50% of total US beef production (https://quickstats.nass.usda.gov/results/6ED88A30-0BCC-37D0-A6D3-5B0BE7A680CD). The diverse ecosystem services scenario may initially develop in the areas where regulatory and power grid interconnection barriers and land costs to developers are the lowest, and in the Southwest where the adverse impacts of climate change and the potential for solar energy generation will be greatest. The amenity ranching scenario will be interspersed throughout US rangelands in locations where amenity values far exceed revenues derived from agricultural production. Rural communities, economies and lifestyles will be variously modified in this scenario, especially when ranch subdivision occurs in high-amenity-value areas and near urban centres. Accordingly, these scenario trajectories are anticipated to co-occur at various locations and times to produce varied and complex outcomes. Interactions among the grass-finished beef and modern pastoralism, and diverse ecosystem services and amenity ranching scenarios may be most likely to co-occur, but all possible interactions can be envisioned.

The grass-finished beef and modern pastoralism scenarios may sustain existing rural communities by continuing to produce beef products to supply societal demand. However, the production capacity, economic viability and associated market price of beef represent major uncertainties for these scenarios. An increase in demand-side challenges associated with human diets and health, animal welfare, antimicrobial resistance, and genetic modification and biotechnology, in addition to previously stated environmental concerns, may contribute to a decline in beef consumption in the United States and other affluent nations[22]. By contrast, the diversified ecosystem services and amenity ranching scenarios may transform rural communities and economies through the expansion of renewable energy generation, a growing service industry and the infusion of external capital from amenity landowners. The expansion of wind and solar energy generation may present landowners with alternative sources of income, and communities with energy independence and diversified employment opportunities. The consequences of the amenity ranching scenario on rural communities are difficult to assess because the proportion of positive and negative outcomes will vary with the commitment of amenity owners to continued livestock production and the sustainability of local communities. This scenario is anticipated to have the greatest potential to transform the rural West by shifting landownership, replacing family-owned ranches and disrupting existing ranch culture.

Scenario assessments frequently include intervention strategies designed to promote or avert various outcomes based on their perceived impact on society[6]. However, in this case, appropriate interventions are difficult to envision given the potentially substantial, but uncertain, impacts of the biophysical and societal drivers contributing to the scenario trajectories. In addition, the relative consequences of these four scenarios are difficult to assess, because future societal demand for ecosystem services and societal willingness to reprioritize those demands are both ill-defined. Furthermore, the existence of tipping points has the potential to abruptly alter scenario trajectories in unanticipated ways (Box 2). Tipping points occur when small quantitative changes initiate nonlinear processes that lead to major system change[59].

BOX 2

Tipping points may accelerate scenario trajectories

Tipping points occur when small quantitative changes initiate a nonlinear process of transformation that leads to a qualitatively different state of the system, which is often irreversible[59]. An alternative system state often necessitates a transition to alternative ecosystem services and livelihoods. Triggers describe distinct events that initiate critical system change and include both biophysical and social processes and their interactions. The following tipping points and triggers would substantially accelerate the trajectories of the four identified scenarios.

Tipping point. Family-owned beef cattle ranches diminish to the point they no longer support infrastructure, markets and desired lifestyles necessary to maintain the culture of rural ranching communities. The loss of cultural identity further incentivizes ranch sales for alternative land uses, especially amenity services, biodiversity conservation and renewable energy generation[19,58].
Potential triggers. High investment value of rangelands, low profit margins of cattle ranches, insufficient intergenerational ranch transfer, and increased frequency and severity of climate extremes.

Tipping point. Rapid expansion of renewable energy development transforms local and regional communities through economic growth, expanding income streams to landowners, diversified employment opportunities and demographic influx (https://cleanpower.org/facts/state-fact-sheets/).
Potential triggers. Technological advances, power grid improvements, and reduced permitting and siting barriers to renewable energy deployment, increasing priority to mitigate GHG emissions, greater power demand through electrification; and decommissioning of ageing energy infrastructure, especially coal-fired facilities.

Tipping point. Greater demand for human food security necessitates major modifications to agricultural programmes and policies that prioritize food production over that of livestock feed. New incentive structures will generate rapid, large-scale changes in arable land use to increase sustainable food production[23].
Potential triggers. Crop yields insufficient to meet increasing demand, increased frequency/severity of drought, social or political disruption, armed conflict, and disease/pathogen outbreaks affecting humans, livestock or crops.

Tipping point. Continued or worsening megadrought in the West will adversely impact the supply of all rangeland ecosystem services, which will produce cascading effects throughout the national economy. Megadrought expansion into the Great Plains will adversely affect both crop and beef cattle production to negatively affect rural communities and national food security[60].
Potential triggers. Increasing frequency and intensity of climate anomalies accentuated by insufficient adaptation planning, adaptive capacity and governance to mitigate impacts.

The potential consequences of these scenarios, either independently or in combination, will affect food and energy security, environmental quality, cultural identity and livelihoods. Technological solutions alone may be insufficient to chart a sustainable path forwards and will require substantial shifts in societal priorities and values[60]. Consequently, transformational change of social-ecological systems, as opposed to small and incremental change within systems, may be required to sustainably accommodate large changes in the availability of ecosystem services[61,62].

'Transformative science with society' represents an approach that employs collaborative partnerships to address power inequities, ethical concerns and different ways of knowing to deliberately transform social-ecological systems[62]. Collaborative rangeland partnerships will need to engage diverse social organizations, including private, state, federal agencies and Tribal Nations, and non-government organizations, to effectively guide this transformation. The evolving consequences of these scenario trajectories may create 'windows of opportunity' for system transformation by necessitating extensive social innovation, and development of new narratives of human–nature relationships and innovative leadership[60,62].

Development of region-specific scenarios, involving sustained commitment and communication among diverse stakeholders and societal interests, may be an effective strategy to facilitate progress towards planned transformation of social-ecological systems. Forward-thinking research and policy analyses will be needed to support development of consequential regional scenarios. Increased recognition and inventory of the diverse societal benefits provided by rangeland ecosystem services is a critical prerequisite. Greater awareness of the impact of increasing biophysical and societal change on the supply of ecosystem services is needed to minimize unanticipated, disruptive outcomes and to support development of proactive mitigation and allocation strategies. The scope and complexity of this challenge will require accelerated development of collaborative, adaptive social organizations to identify, assess, and manage trade-offs among ecosystem services, and to equitably prioritize food and energy security, environmental quality and cultural identity.

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Acknowledgements

We thank D. Pyke with the US Geological Survey for their valuable contributions to an earlier version of the paper. Any use of trade, firm or product names is for descriptive purposes only and does not imply endorsement by the US Government. S. Kagone created Fig. 1, M. Joyce created Fig. 2, and A. Briske and E. Raynor revised Boxes 1 and 2.

Author contributions

D.D.B. proposed the initial concept and led the paper writing. S.R.A., E.B., W.B., J.D.D., H.G., J.H., C.E.K., M.K., T.J.L., P.N., O.S., N.F.S. and K.R.S.-L. contributed to paper development and revision in their specific areas of expertise.

Competing interests

The authors declare no competing interests.

Additional information

Correspondence should be addressed to David D. Briske.

Peer review information *Nature Sustainability* thanks the anonymous reviewers for their contribution to the peer review of this work.