Rangeland Ecology & Management 77 (2021) 17–29

Contents lists available at ScienceDirect

Rangeland Ecology & Management

journal homepage: www.elsevier.com/locate/rama

Assessing Sustainability Goals Using Big Data: Collaborative Adaptive Management in the Malpai Borderlands

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ARTICLE INFO

Article history:
Received 25 September 2020
Revised 6 February 2021
Accepted 2 March 2021

Keywords:
big data
fire
plant production
ranch turnover
rangeland-cropland conversion
sustainability

ABSTRACT

Collaborative adaptive management is a means to achieve social and ecological goals in complex natural resource management settings. Evaluation of collaborative management outcomes, however, is difficult at the scale of large landscapes. We developed an approach for such evaluations using long-term, spatio-temporal gridded or county-level datasets alongside local information on changes in ranch ownership. We applied this approach to evaluate the sustainability goals of the Malpai Borderlands Group (MBG) by comparing the MBG landscape to surrounding, similar desert grassland landscapes. We matched datasets, where possible, to management goals, including the preservation of ranching livelihoods, prevention of rangeland fragmentation by exurban development, sustaining the ecological role of fire, limiting or reversing woody plant encroachment into grasslands, sustaining rangeland productivity, and sustaining biodiversity. We found that the number of ranch families changed little since MBG was established, although several ranches were consolidated within some families or absentee owners, such that multiple families share other ranches. The number of beef cattle ranches declined within one MBG county, likely due to increasing depth to groundwater. Exurban development and rangeland-to-cropland conversion have been virtually nonexistent in the MBG landscape, while such conversions are common in adjacent landscapes. Coordinated fire planning with low fragmentation of rangeland has led to extensive fires in the MBG landscape, dwarfing the area burned in adjacent landscapes. The percent of land area exhibiting significant trends of increasing bare ground cover was intermediate in the MBG landscape compared with adjacent landscapes, while herbaceous and shrub cover exhibited significant trends in only a small fraction of the study region. Rangeland productivity exhibited significant declines in some landscapes, but declines were minimal in the MBG area. Our analysis suggests that collaborative adaptive management implemented by the MBG has aligned with their goals, but changing climate, water availability, and demography will become increasingly challenging.

Introduction

Collaborative adaptive management (CAM) involves coordinated goal identification and shared knowledge, decision making, and learning by communities that often have diverse interests in natural resources (Duff et al. 2009; Fernández-Giménez et al. 2019). In rangelands, diverse interests can lead to conflict when the objectives and decisions of ranchers, environmental interest groups, and government land managers are not adequately coordinated (Scarlett 2013). Coordinated decision making is especially challenging at the scale of large landscapes of the western United States, involving mixed private, state, and federal ownership, multiple government agency jurisdictions, landowners and lessees with varying perceptions and values, and intense, contrasting interests among different stakeholders in preservation, recreation, and ranching (Sayre 2005; Butler et al. 2015). CAM aims to increase participation and coordination in management decisions to reduce conflict and facilitate progress toward shared management goals (Keough and Blahna 2006).

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https://doi.org/10.1016/j.rama.2021.03.002
1550-7424/Published by Elsevier Inc. on behalf of The Society for Range Management.

Table 1
Sustainability goals of the Malpai Borderlands Group adapted from McDonald (1995) and corresponding metrics evaluated in this paper.

Goal	Metric evaluated
1. Preserve ranching livelihoods	Number of beef cow cattle operations, National Agricultural Statistics Service and changes in ranch ownership within the MBG
2. Prevent rangeland fragmentation by exurban development	Change from rangeland to cropland/urban uses 2008-2018; Cropland Data Layer, National Agricultural Statistics Service
3. Sustain the ecological role of fire	Cumulative proportion of area burned 1994-2015; spatial wildfire occurrence data for the United States, 1992-2015, 4th edition
4. Limit or reverse woody plant encroachment in grasslands	Perennial herbaceous and shrub cover 1994-2018, Rangeland Analysis Platform 1.0
5. Sustain rangeland productivity	Annual rangeland production 1994-2018, Rangeland Production Monitoring Service
6. Sustain biodiversity	No data at a suitable scale

The evaluation of CAM effects on natural resources and society requires assessment of attributes related to stakeholder goals at appropriate scales (Conley and Moote 2003; Clement et al. 2020). Few such evaluations exist (e.g., Rissman and Sayre 2012; Ulambayar et al. 2017; Augustine et al. 2020), reflecting the difficulty of measuring long-term trends and conducting comparisons at the scale of large, complex landscapes. Large landscapes encompassed by a CAM effort cannot usually be replicated for experimentation (Hargrove and Pickering 1992; Turner 2005). Furthermore, field monitoring data of sufficient standardization, duration, and spatial stratification are seldom available, even though strides have been made toward this goal (Herrick et al. 2010). The recent availability of "big data" resources, however, provides new opportunities for such evaluations. Several big data resources leverage spatial data layers, remote sensing, and standardized field data to create gridded estimates of biophysical variables at fine scales (e.g., 900 m^2–4 km^2) and at a continental extent. In the case of dynamic variables, including climate and vegetation, estimates have been produced over long time periods (1984–present) at annual resolution (Bestelmeyer et al. 2020). Other resources reflect the increased availability of long-term socioeconomic data gathered by federal agencies such as the National Agricultural Statistics Service. These big data provide an opportunity for quantitative comparisons at the scale of landscapes and can be complemented by locally collected "small" data reflecting other community goals.

We applied our analysis approach to evaluate the progress of the Malpai Borderlands Group (MBG) toward its stated goals over a 25-yr period. MBG is among the oldest and most storied of CAM efforts in rangelands (Keough and Blahna 2006; Brunson and Huntsinger 2008) and was established in 1994 to address the interrelated concerns of ranch sustainability, land subdivision and conversion, and shrub encroachment into grasslands of southeastern Arizona and southwestern New Mexico (McDonald 1995; Sayre 2005). The MBG has several interrelated sustainability goals (Table 1) ultimately dependent on preventing land fragmentation by exurban development (Goal 2). Fragmentation limits options for the management of extensive fires that are needed to limit shrub encroachment (Goal 3, Goal 4). In turn, shrub encroachment (by mesquite, *Prosopis glandulosa*, *P. velutina*, and creosotebush, *Larrea tridentata*) into Southwestern desert grasslands can cause reductions of grass productivity (Goal 5), forage availability for livestock, soil protection from erosion, and abundances of grassland-dependent animal species (Goal 6) (D'Odorico et al. 2012; Coffman et al. 2014; Bestelmeyer et al. 2018). The sustainability of ranching livelihoods (Goal 1) ultimately depends on adequate forage supply across ranch enterprises and meeting federally mandated rangeland health goals on public lands leased for grazing.

MBG uses three primary tools to attain sustainability goals. First, the MBG coordinates funding and logistical support for conservation easements to limit land conversion and to promote rangeland health (Rissman and Sayre 2012). Fifty-two percent of the ≈800 000-acre MBG planning area is private land, and the remainder is federal and state land. Of the private land, 70% has a conservation easement as of 2020. Second, the MBG cooperates with federal and state agencies in fire management, such that there are clear procedures for communication between ranchers and agency fire officials when responding to wildfire and conducting prescribed fires. Agencies and landowners representing a majority of the MBG planning area currently allow wildfires to spread if they align with management objectives. Third, ranchers, agency staff, representatives of environmental organizations, and the public coordinate on management and restoration activities and share knowledge. In 2008, an MBG-specific Habitat Conservation Plan was developed that facilitates the appropriate use of prescribed fire and other management activities considering requirements of the Endangered Species Act (Malpai Habitat Conservation Plan Technical Working Group and Lehman 2008). Staff from federal agencies and The Nature Conservancy have long-term relationships with ranchers, promoting trust. Annual board and agency meetings address topics such as easements, agency policies, drought conditions, and restoration funding opportunities. The annual science meeting is open to the public and provides opportunities for the exchange of knowledge among scientists, ranchers and agency staff, and the regional public.

Although the MBG was not designed by scientists and is instead a grassroots effort, its activities broadly conform to CAM principles, emphasizing feedbacks among monitoring, social learning, and management (Fernández-Giménez et al. 2019). Expectations for what constitutes CAM need to account for activities that can reasonably be supported in a large landscape circumscribing multiple agricultural enterprises and government agencies. CAM in MBG occurs in the context of polycentric governance, defined as having multiple, nested governing authorities at different scales and with overlapping jurisdictions (Andersson and Ostrom 2008; Biggs et al. 2012). Three scales of decision making can be recognized: 1) independent ranching families that manage according to enterprise-scale goals, influenced to varying degrees by landscape-scale goals of government agencies and the MBG as a whole; 2) ranchers and local agency representatives that coordinate on management actions involving shared landscape-scale goals; and 3) national institutions, including government natural resource agencies and environmental organizations, that advance national-to-global sustainability goals at the local scale via financial support (Sayre 2005) or that impose policies that affect rancher and local agency goals, such as via the government agencies responsible for border security measures (Sayre and Knight 2010). Consequently, CAM as practiced by the MBG must also be considered with respect to management decisions at different scales. Ranchers take advantage of vegetation monitoring and long-term experiments in parts of the MBG planning area to better understand the drivers of rangeland condition that influence their enterprise-scale adaptation strategies (Curtin 2008; Curtin 2011). At the scale of MBG, experiments on the effects of fire on endangered species have led to social learning by ranchers and agency staff alike and the adaptation of fire management protocols (Malpai Habitat Conservation Plan Technical Working Group and Lehman 2008; Gottfried et al. 2009). Other forms of learning and adaptation are equally important, such as how to manage turnover in agency staff or manage MBG investments in conservation easements. A detailed analysis MBG activities awaits further study, but for purposes of this paper, we feel that it is fair to characterize these activities as CAM.

Here, we employ a “big data” comparative approach alongside local information to evaluate MBG’s CAM activities over 25 yr. We compare the MBG planning area (hereafter “landscape”) to adjacent desert grassland landscapes with similar climates and landforms, delineated using Land Resource Units of the National Cooperative Soil Survey (Salley et al. 2016) that overlap with the MBG landscape. Each MBG sustainability goal was matched, where possible, to a suitable dataset (Table 1). Trends were compared among landscapes and, in the case of ranch turnover, reported for the MBG landscape for the first time. A number of caveats regarding our approach are necessary. First, we recognize that some big data resources are new (especially rangeland productivity and vegetation cover) and untested, save for the validations used in creating the models. Undoubtedly, these tools will be improved with additional field data and new computational approaches (e.g., Allred et al. 2020) and the results we report may change accordingly in the future. Our data sources do, however, represent the best science information available at the extent of the desert grassland region and that is long term. Second, we cannot assert that any differences among landscapes that we observe are due exclusively to MBG CAM activities. Despite the fact that all landscapes considered are dominated by desert grassland vegetation (McClaran and Van Devender 1995; Bestelmeyer et al. 2018), there are inherent differences in ecological potential, societal context, and management history that likely influence (or even dominate) most of the differences we observe. In the case of National Agricultural Statistics Service data at the county level (see later), MBG activities can at best be considered a partial influence. Nonetheless, we can ask whether the comparisons of time series data among landscapes *are consistent with* sustainability goals as a first step toward understanding the impacts of, and challenges to, the MBG. Finally, we do not have the data to evaluate differences in ranch-scale management within and outside of the MBG landscape over the 25-yr period. Consequently, we cannot address the specific management-related mechanisms involved in any differences among landscapes we observe.

Specifically, we hypothesized the following: 1) the number of beef cattle operations in counties with MBG ranches will be stable over time, consistent with ranch sustainability in the broader region, and MBG ranches in 1994 persist in the present as family-owned cattle operations; 2) the area converted from rangeland to more intensive uses (cropland, urban) will be lower in the MBG landscape compared with surrounding landscapes, due to the adoption of conservation easements; 3) the rangeland area burned will be greater in MBG than surrounding landscapes, reflecting the impact of fire coordination plans for allowing beneficial fires to spread; 4) perennial herbaceous cover has increased and shrub cover has decreased to a greater degree in MBG than surrounding landscapes due to the effects of fire and other management actions, including hydrological restoration and brush management; and 5) rangeland productivity is stable or increasing to a greater degree in MBG than surrounding landscapes due to proactive management. We conclude by discussing the implications of our results for the future of the MBG and for similar evaluations in other rangelands.

Methods

The desert grassland region

The MBG landscape straddles southwest New Mexico and southeast Arizona on the border of Mexico, within the desert grassland region of the Southwest (Fig. 1). Historically, rangeland ecosystems in the region were typically dominated by warm-season perennial grasses on all but the hottest, thinnest, or rockiest soils and featured scattered woody plants. The predominant grassland or savanna aspect was maintained by fire, which requires highly connected grass cover as fine fuels (McClaran and Van Devender 1995; Okin et al. 2009). Drought and overgrazing episodes of the past triggered soil degradation and rapid shrub encroachment in many areas, limiting perennial grass production and connectivity and thereby limiting the potential for fire to stabilize or reduce shrub cover and promoting soil erosion. This has led to a continuing trend of shrub cover increase in many areas where landscapes have been intensively monitored, and some areas have become saturated with shrubs with little to no grass cover (McClaran et al. 2010; Browning et al. 2012; Bestelmeyer et al. 2018).

Past and ongoing ecological changes, compounded by a progressively drying climate (Williams et al. 2020), create challenging social and economic conditions for Southwestern US ranchers (Havstad et al. 2016). These challenges are associated with shifts from small and medium-sized family ranches to amenity and corporate ranches or to the subdivision of deeded portions of ranches for exurban development (Gosnell and Travis 2005; Brunson and Huntsinger 2008; Munden-Dixon et al. 2019).

Landscape comparisons

We used land resource units (LRUs) of the National Cooperative Soil Survey as a basis for comparisons with the MBG landscape. LRUs are mapped at scales of 1:250 000–1:60 000 and are differentiated based on regional climate, geology, geomorphology, soil great groups, and subgroups (Salley et al. 2016). In our study region, these LRUs all harbor desert grassland vegetation but differ in average annual rainfall, grass productivity/composition, and the overall cover and type of woody plants. We did not consider portions of one LRU (42.2) extending into Texas, which differs from New Mexico and Arizona in the amount of public land and, consequently, management and data reporting (Levi and Bestelmeyer 2016).

Following conventions of the National Cooperative Soil Survey, LRUs are nested inside a Major Land Resource Area (MLRA) and denoted after the decimal. The LRUs considered in this study include MLRA 41.1 (Madrean oak savanna, 12–16” precipitation zone); 41.2 (Sonoran Desert shrubs, 8–12”); 41.3 (Chihuahuan/Sonoran semidesert grasslands, 12–16”); and 42.2 (Chihuahuan Desert shrub, 7–12”). Each of these LRUs are represented to varying extents in the MBG landscape. We compared the MBG landscape as a whole to the non-MBG portions of each of the aforementioned LRUs (Fig. 1). Gridded (vegetation, climate, land use) and point (fire) data were compared among each of the five landscapes. In addition, we compared the counties within the MBG planning area (Cochise, Arizona and Hidalgo, New Mexico) with surrounding counties containing desert grassland vegetation (Fig. 2). Note that the majority of the MBG landscape lies within MLRA 41.1, so the comparison of MBG with the non-MBG MLRA 41.1 landscape is assumed to minimize inherent abiotic differences.

Datasets and analyses

Sustainability goals were each associated with a multitemporal dataset except for the maintenance of biodiversity, for which even county-level multitemporal data were unavailable.

Goal 1

The number of beef cattle operations by county from 2002 to 2017 was accessed from the Census of Agriculture administered

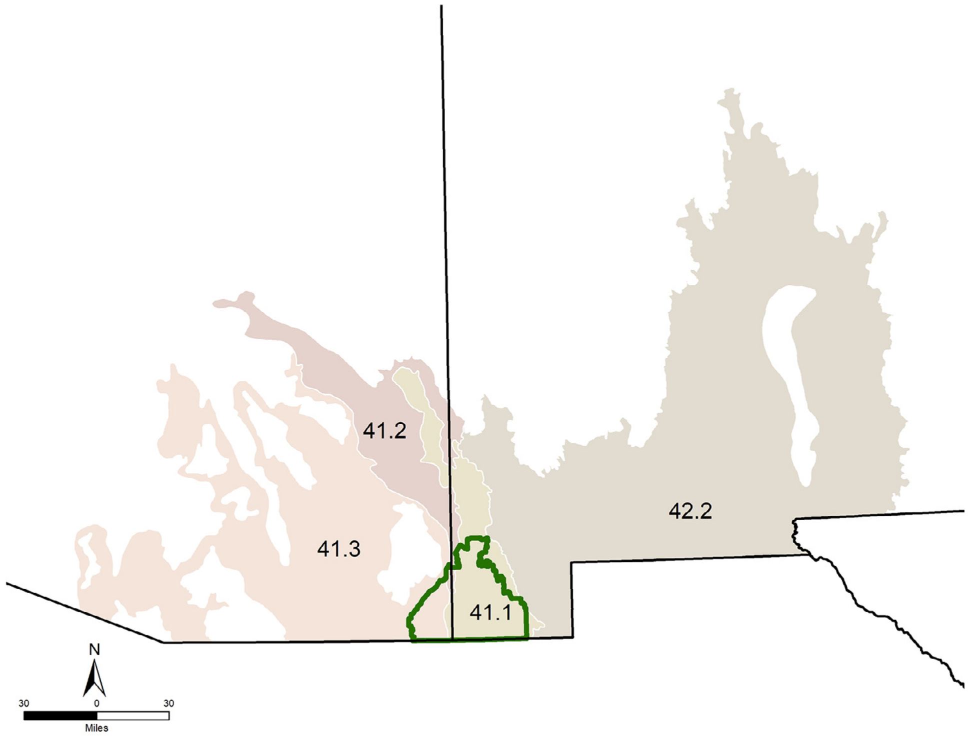

Figure 1. The Malpai Borderlands Group (MBG) landscape (green outline) with respect to Land Resource Units considered in this study. The Arizona/New Mexico state line is in the center of the image.

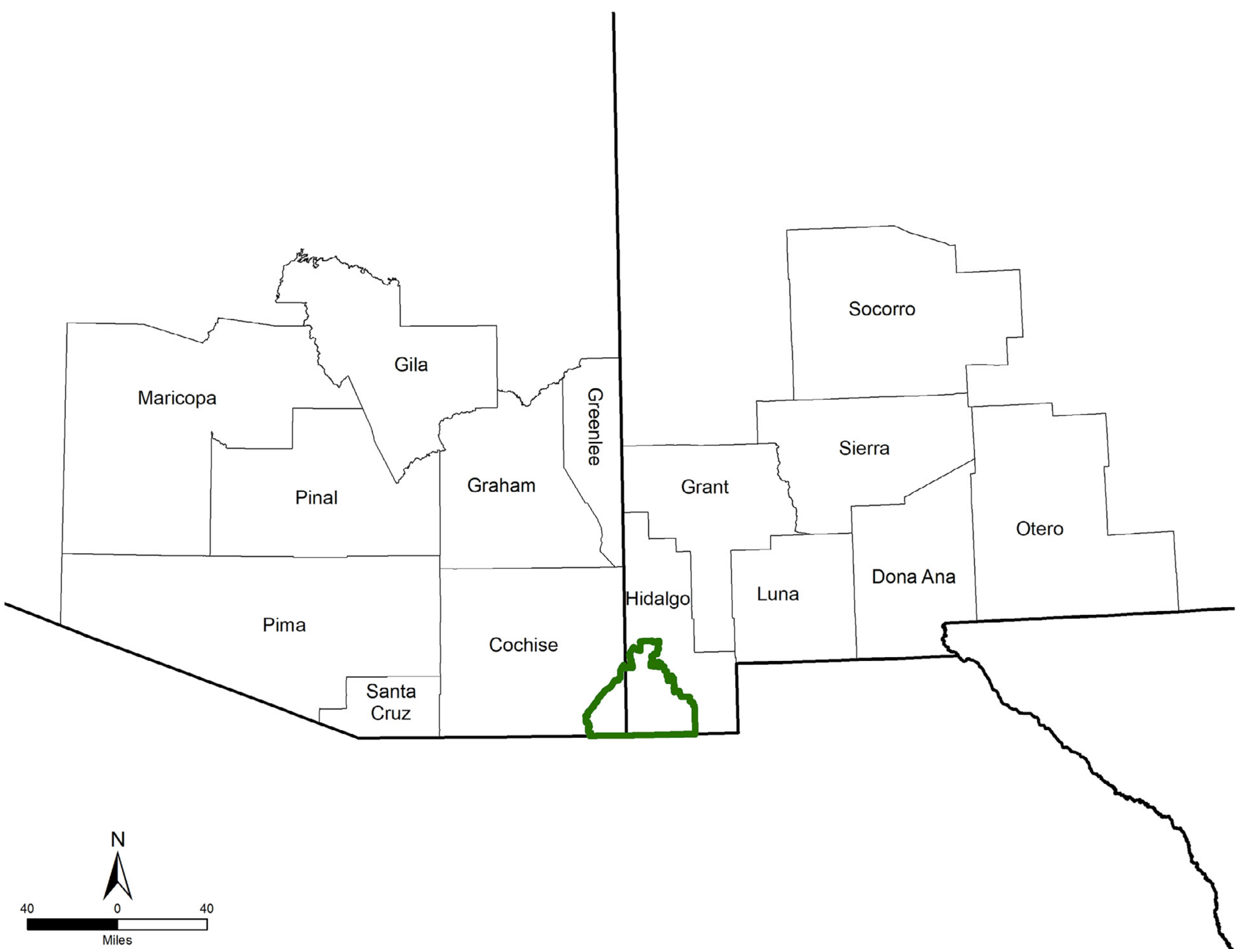

Figure 2. The Malpai Borderlands Group landscape (green outline) with respect to counties overlapping with Land Resource Units in this study.

by the US Department of Agriculture National Agricultural Statistics Service (2020b). The data come from the Cattle, Cows, Beef-Operations with Inventory data item in the Inventory of Beef Cows domain. We summed values in domain categories from 10 to 500 head and excluded 1–9 head operations, reasoning that the former was most likely to reflect ranches obtaining substantial income from livestock. For this analysis, we compared Cochise and Hidalgo with Graham, Grant, Greenlee, and Luna counties that are immediately adjacent (see Fig. 2) and are similar with respect to the degree of urbanization. We used all years in our study period for which size categories were available (2002, 2007, 2012, 2017). Moreover, we selected beef cow operations because cow-calf ranching is generally more prevalent than stocker production in the study area (Havstad et al. 2016).

In addition, we tracked the fate of 35 ranches in the MBG planning area from 1994 to 2020 based on informal interviews of long-time residents conducted by MBG staff. Changes in ranch ownership were classified as follows: 1) continued ownership by the original family (i.e., owners and extended family members), 2) sale/transfer to another family member (child or relative), 3) sale to a family that immigrated from outside the MBG area, 4) sale to another family in the planning area, 5) sale to an absentee landowner (i.e., that did not reside in the MBG planning area), and 6) sale from one absentee to another absentee owner. Note that all current ranches within the planning area participate in MBG activities except for three located in the center of the planning area.

Goal 2

Land use changes from 2008 to 2018 (2008 being the earliest comparable records available) were estimated using the Cropland Data Layer (CDL) datasets available from USDA National Agricultural Statistics Service (2020a). Rangeland, cropland, and built-up (urban) land uses were mapped for each year in the time series by assigning the original CDL classes to one of these three general categories or to a residual "other" category (Bestelmeyer et al. 2015). One-way, one-time shifts from rangeland to cropland, cropland to rangeland, and non-built-up to built-up were identified on a per-pixel (30 m) basis (Lark et al. 2015). Pixels were grouped if they exhibited the same type of conversion and touched at either a side or corner, and only groups 45 pixels (≈4 ha) or larger were included in calculations of converted area.

Goal 3

Fire data from 1994 to 2015 were accessed from the Short database (Short 2017), which includes fire start date and area burned represented by one point in the landscape. Unlike other national databases, the Short database includes fires < 400 ha in size. Point data were intersected with the landscape polygons, and all fire information was summarized according to these intersections.

Goal 4

Changes in vegetation fractional cover at the extent of landscapes were estimated using the Rangeland Analysis Platform (RAP) version 1.0 (Allred and Jones 2020). For calculating mean fractional cover in each landscape, we considered the period from 1994 to 2018. We followed Jones et al. (2020) in using data only from 1999 to 2018 for pixel-level trend estimation because this period provided greater satellite data coverage compared with earlier years, resulting in fewer data limitations that could adversely affect trend estimates. RAP estimates fractional cover in rangelands of the western United States at a 30-m resolution, using machine learning algorithms applied to tens of thousands of standardized local observations of foliar cover linked to remotely sensed and modeled covariates (Jones et al. 2018). Our focus here was on three cover types: 1) bare ground, 2) perennial grasses and forbs, and 3) shrubs. Pixels intersecting landscape boundaries were excluded from analysis, and only pixels with no missing values over the 25-yr period were analyzed. We followed precisely the procedures used in Jones et al. (2020) to assess statistical significance of trends. Pixels with significant trends met two criteria: 1) a significant trend determined by Kendall's Tau-b rank correlation ($\alpha = 0.10$) and 2) a percent change over time greater than the mean absolute error of the fractional cover in the RAP version 1.0 dataset. The mean absolute error values are available in Allred et al. (2020). The percent of rangeland area experiencing significant trends were reported (Jones et al. 2020). Google Earth Engine was used to calculate trends and percent area with significant trends (Gorelick et al. 2017).

Goal 5

Changes in rangeland production from 1994 to 2018 were estimated using the Rangeland Production Monitoring Service (RPMS) dataset available at Reeves and Lankston (2020). RPMS is based on Landsat Normalized Difference Vegetation Index data calibrated using ecological site-level production estimates in the SSURGO database (Reeves et al., 2021). RPMS is provided at a 250-m pixel size. The same pixel inclusion rule in Goal 4 was used here, and trends were considered significant using Kendall's Tau-b rank correlation ($\alpha = 0.10$) and the percent area experiencing significant trends reported, similar to Goal 4 above. R software was used to calculate trends and percent area with significant trends (Evans 2020).

In addition, we compared climatic trends among landscapes using the gridMET dataset, which provides numerous climate variables daily at a 4-km^2 resolution for the contiguous United States (Abatzoglou 2020). Pixels occurring within each landscape were included for analysis only if they were covered by 75% or more of rangeland as defined by the RPMS dataset, thereby excluding some areas in river valleys and small mountain ranges. The climate variables were used to provide context for interpreting changes in vegetation cover and production, and trends were evaluated using Thiel-Sen regression and Kendall's Tau ($\alpha = 0.10$) for statistical significance.

We were unable to locate a dataset representing trends in biodiversity spanning the study region. Nonetheless, trends in vegetation cover (especially changes in bare ground, shrub, and perennial grass/forb cover) should reflect critical changes in habitat supporting biodiversity (Muldavin et al. 2001). For example, the cover of bare ground and grasses are the dominant predictors of grassland bird habitat use (Fisher and Davis 2010).

Results

Goal 1

The number of beef cow operations declined by about 50 in Cochise County from 2002 to 2007 and increased slightly in Hidalgo County, tracking the variable trends of adjacent counties (Fig. 3). The higher overall number of operations in Cochise County, Arizona is due to a larger number of smaller operations, perhaps linked to corn and hay production that occupies over 6 × more area than in Hidalgo County (www.nass.usda.gov/AgCensus/).

Within the MBG landscape, ownership change occurred in 66% of the original 35 ranches since 1994, but all of these ranches still exist and have maintained grazing leases on public land. Most ranches where ownership change occurred were transferred to other families (23%) or family members (20%). Eleven percent of

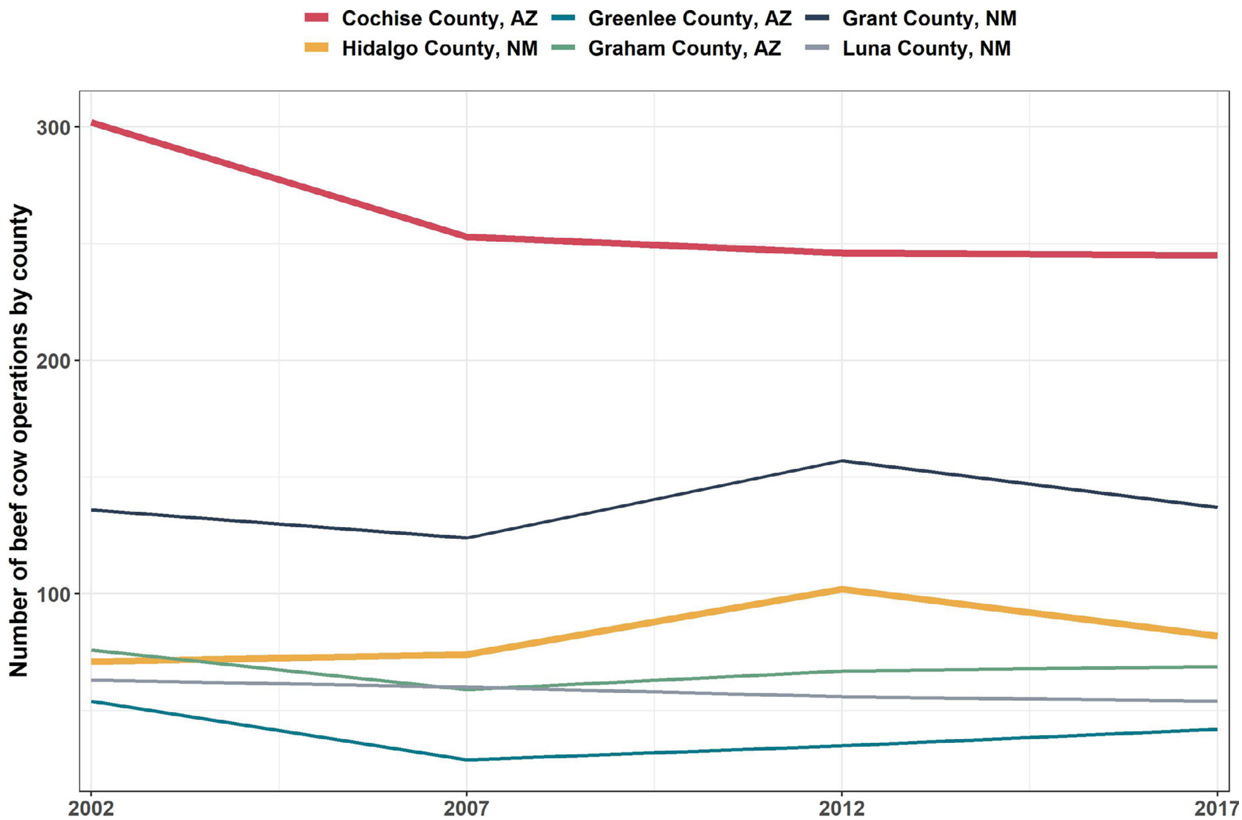

Figure 3. Change in number of operations with beef cows with ≥ 10 head from 2002 to 2017 in MBG counties (Cochise and Hidalgo, thick lines) and four immediately surrounding counties for reference.

ranches were sold to absentee owners, 9% to families that immigrated from outside the MBG area, and 3% (one ranch) was sold from one original absentee owner to another absentee. The number of local families managing ranches within the MBG landscape changed little from 1994 to 2020 (from 35 to 34 families). Excluding ranches that are now absentee owned (5) or were transferred to existing families (8), remaining ranches (22) now support ≈1.5 families on average.

Goal 2

The rate of land conversion from rangeland to cropland from 2008 to 2018 was lowest in the MBG landscape (totaling 35 ha) but was substantial in adjacent landscapes, up to 67 km^2 in the relatively large MLRA 42.2 (Fig. 4). Conversion from rangeland or cropland to built-up was not detected in the MBG landscape or MLRA 41.1 but occurred in adjacent landscapes.

Goal 3

The area burned over 22 yr was vastly higher in MBG (at ≈50% of the total landscape area) than in surrounding landscapes (from 1% to 7%) (Table 2). The density of fires in MBG was intermediate compared with adjacent landscapes, but the area burned per fire was much larger in MBG.

Goal 4

MBG was consistently the warmest and, based on vapor pressure deficit, driest landscape over the 1994–2018 time period (Fig. 5). Despite relatively harsh overall landscape conditions, MBG had lower extents of bare ground and higher perennial grass and forb cover than other landscapes in most years, while shrub cover was intermediate (Fig. 6). Over the entire region, RAP detected a greater area of increasing trends of bare ground than decreasing trends (Fig. 7). The MBG landscape had a greater percent of area featuring increasing bare ground than MLRA 41.3, but the percent area was lower than other landscapes, especially MLRA 41.2. The percent area exhibiting significant trends in perennial grass and forbs was generally low across the study region, but there was a higher percent of area featuring both positive and negative trends in the MBG landscape compared with other landscapes, with the balance slightly favoring areas of increase. The percent area featuring significant trends in shrub cover was very low, usually < 1%.

Goal 5

MBG was the most productive landscape and productivity fluctuated strongly over time (Fig. 8), likely reflecting the complex, lagged responses of grassland production to multiyear wet or dry periods (Petrie et al. 2018). Significant productivity declines were common across the study region, but the percent of rangeland area exhibiting declining productivity was lowest in the MBG and only slightly higher in MLRA 41.3 (Fig. 9). Other landscapes, notably MLRA 41.2, have experienced declining productivity over large areas (**Fig. S1**, available online at doi:10.1016/j.rama.2021.03.002). Trends in summer (growing season, June–September) climate variables were evaluated as context for changing productivity in the MBG landscape (Fig. 10), including total rainfall, mean maximum and minimum daily temperatures, and mean daily vapor pressure deficit. Only minimum daily temperature exhibited a significant trend ($P = 0.02$) over 25 yr, but steep changes were observed in

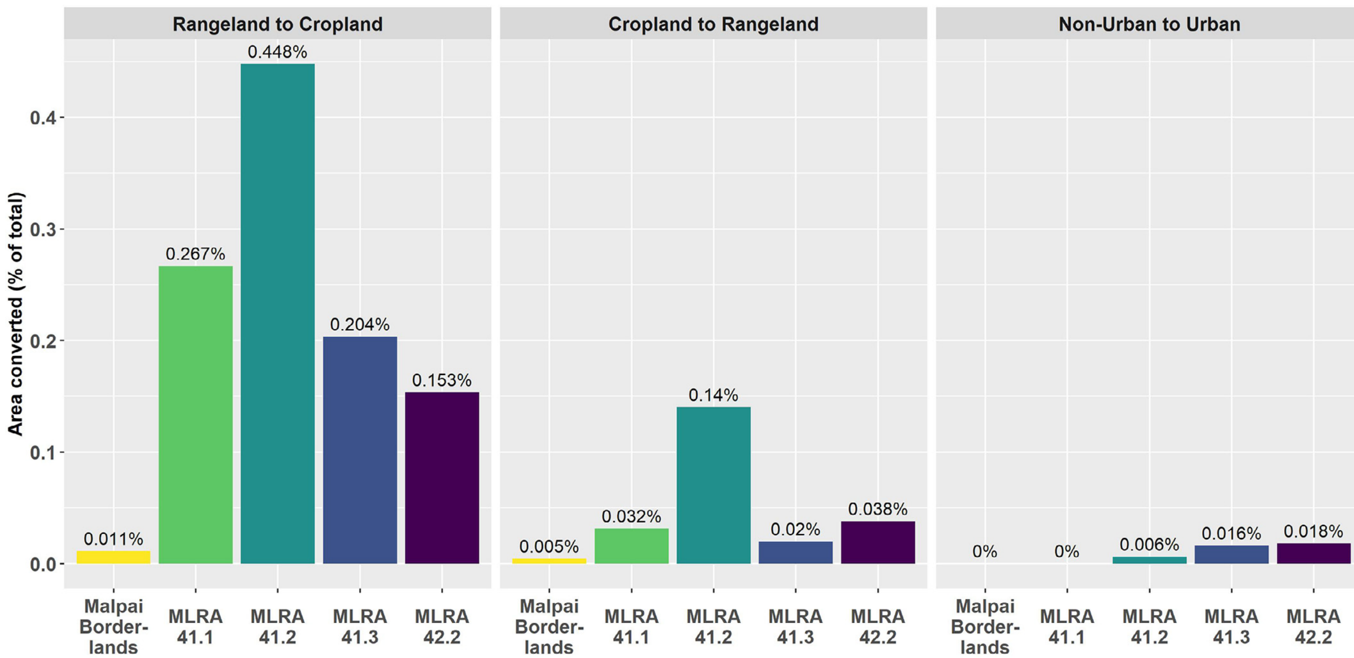

Figure 4. Land use changes in each landscape from 2008 to 2018 from the Cropland Data Layer. Refer to Table 2 for the area of each landscape.

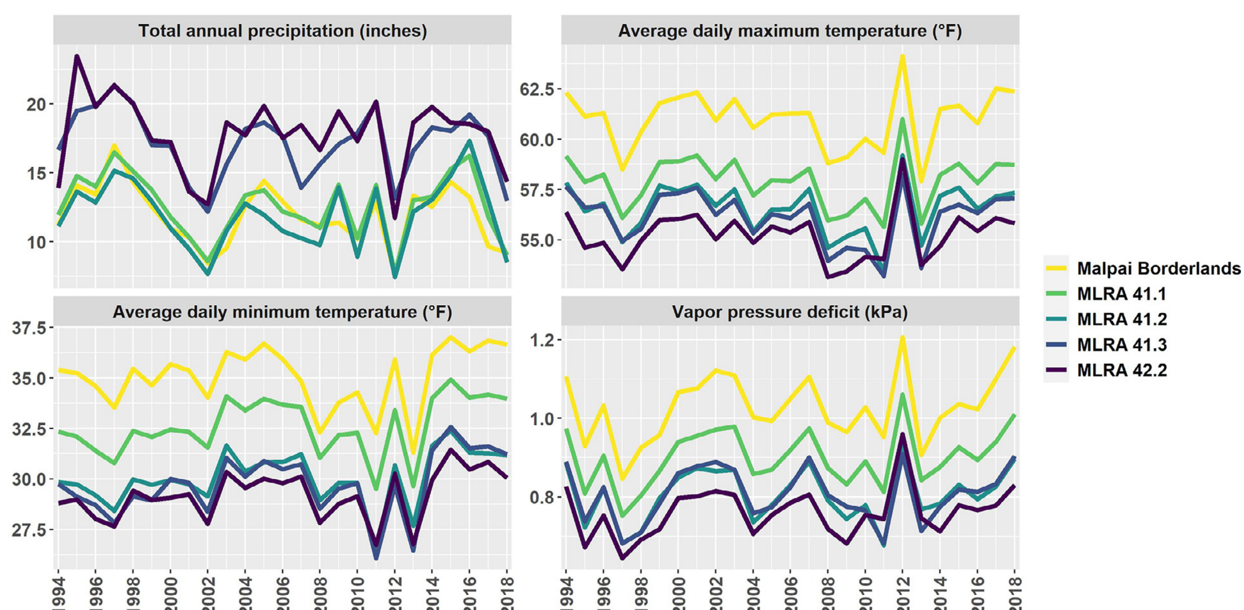

Figure 5. Trends in key climatic variables from 1994 to 2018 averaged across gridMET pixels (4 km^2) occurring within each landscape.

Table 2
Cumulative summary of fires from 1994 to 2015.

Region	Landscape area (km^2)	Total no. of fires	No. of fires > 0.4 ha	Total area burned (km^2)	Density of fires (km^2/fires > 1 acre)	Area burned/fires > 0.4ha (km^2)	Area burned as a proportion of landscape area*
Malpai Borderlands	3 247	150	121	1 669	26.8	13.8	0.51
MLRA 41.1	2 620	86	50	78	52.4	1.6	0.03
MLRA 41.2	6 647	5 175	1 346	80	4.9	0.1	0.01
MLRA 41.3	20 762	3 331	1 330	1 360	15.6	1.0	0.07
MLRA 42.2	43 672	1 004	463	678	94.3	1.5	0.02

* Note that proportions can reflect multiple fires occurring in the same area and should not be interpreted as the proportion of the landscape that has burned at least once; these values are simply total area burned/landscape area.

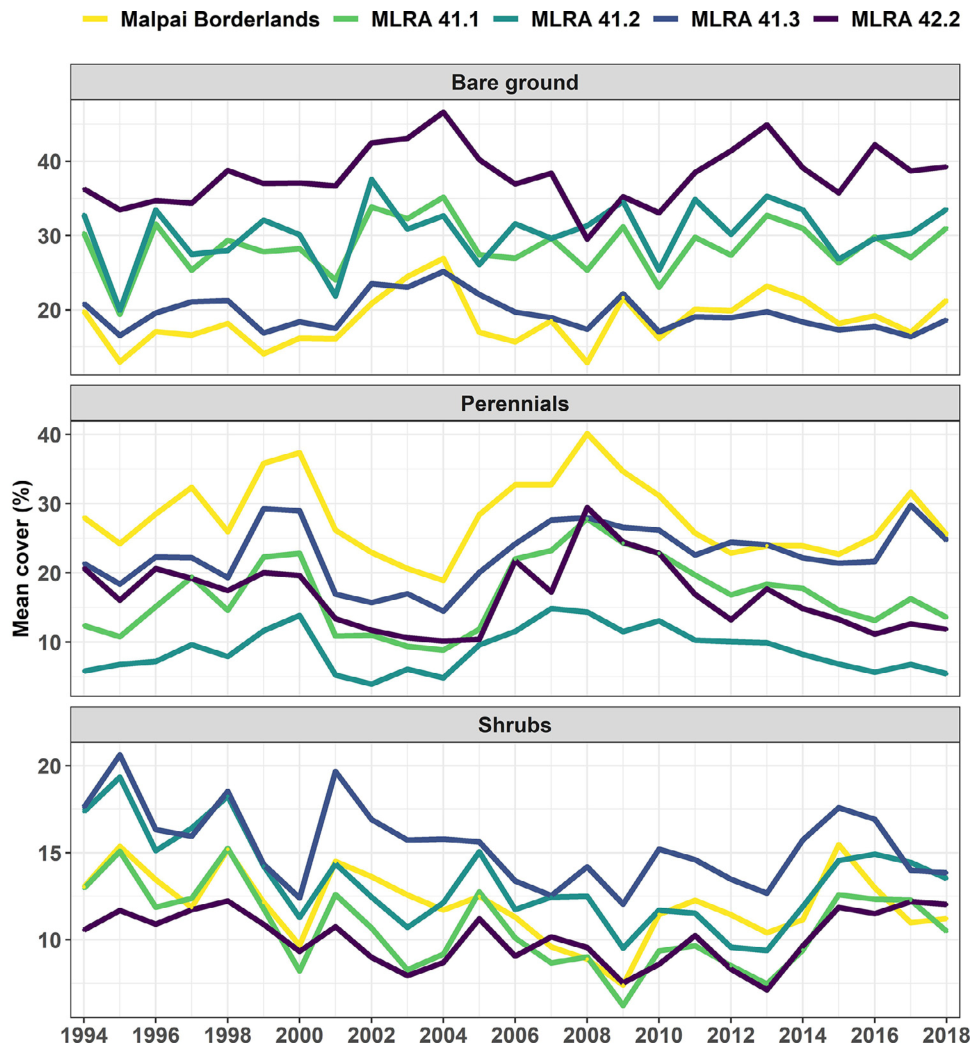

Figure 6. Estimated mean cover of bare ground, perennial grasses and forbs, and shrubs at the pixel level within each landscape from the Rangeland Analysis Platform 1.0 dataset.

the 2014–2018 period. 2018 was the warmest and driest year in the history of MBG.

Discussion

Our comparative "big data" approach suggests that MBG goals established 25 yr ago are largely being met, and certain results strongly support the efficacy of CAM approaches used by MBG.

With regard to the preservation of ranch livelihoods, all ranches in the MBG landscape are still operating as cattle ranches and most continue to be owned and operated by families. Absentee ownership within the MBG landscape has increased, however, reflecting a broader trend in agricultural lands across the United States (Petrzelka et al. 2013). Absentee landowners may be less likely to engage in cooperative management activities, depending on their level of direct involvement (Sorice et al. 2018) and motivations for ranch ownership (Petrzelka and Armstrong 2015). Engagement with absentee owners may require novel strategies in order to sustain management cooperation into the future. It is also notable that the number of families supported by ranches within the MBG landscape was similar in 1994 and 2020, in spite of the transfer of several ranches to absentee landowners and among families. Remaining ranches often support more than one family, perhaps reflecting the increasing importance of shared resources and diverse income sources to sustain ranches in the present era (Sayre 2004; Hamilton et al. 2016).

Despite the apparent resilience of ranch livelihoods taken as a whole in the MBG planning area, we observed a significant decline of beef cattle operations in Cochise County between 2002 and 2007. We cannot attribute this shift confidently to a particular process, but we speculate that it is due largely to agricultural water availability. Water tables in certain areas, such as near Willcox Playa, have been deepening precipitously over the past several decades (Fig. S2, available online at doi:10.1016/j.rama.2021.03.002). Local residents and news reports suggest that small producers, who did not have resources to deepen wells, sold farms to larger corporations and foreign investors (James and O'Dell 2019). The conversion from rangeland to cropland in this part of Cochise County is also apparent in the CDL data (Fig. S3, available online at doi:10.1016/j.rama.2021.03.002). The sustainability of many ranches in the Southwest may ultimately be limited by water availability for ranch operations, as well as regional hay production. Hay is frequently required as supplemental cattle feed during the nongrowing season and in drought periods in the Southwest (Elias et al. 2016; Havstad et al. 2016).

Land use conversion from rangeland to cropland or built-up/urban uses was minimal in the MBG, even though it was substantial in most surrounding landscapes. Land use stability

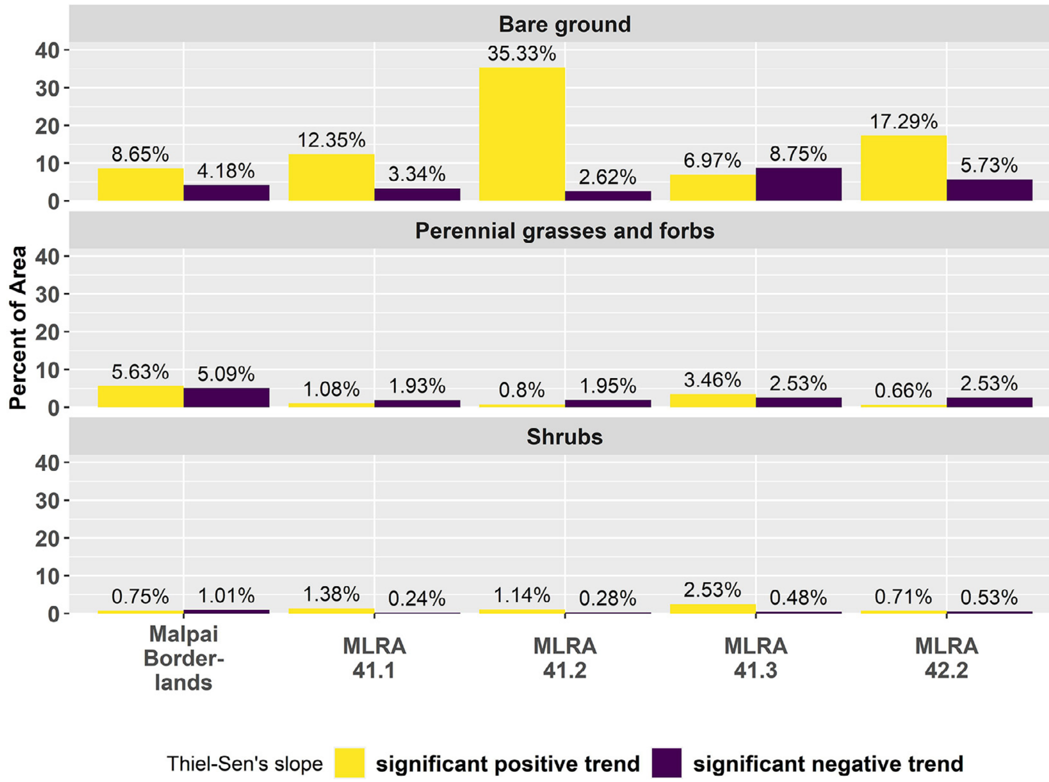

Figure 7. Percent of rangeland area exhibiting significant positive or negative trends in bare ground, perennial grasses and forbs, and shrub cover from 1999 to 2018 in each landscape.

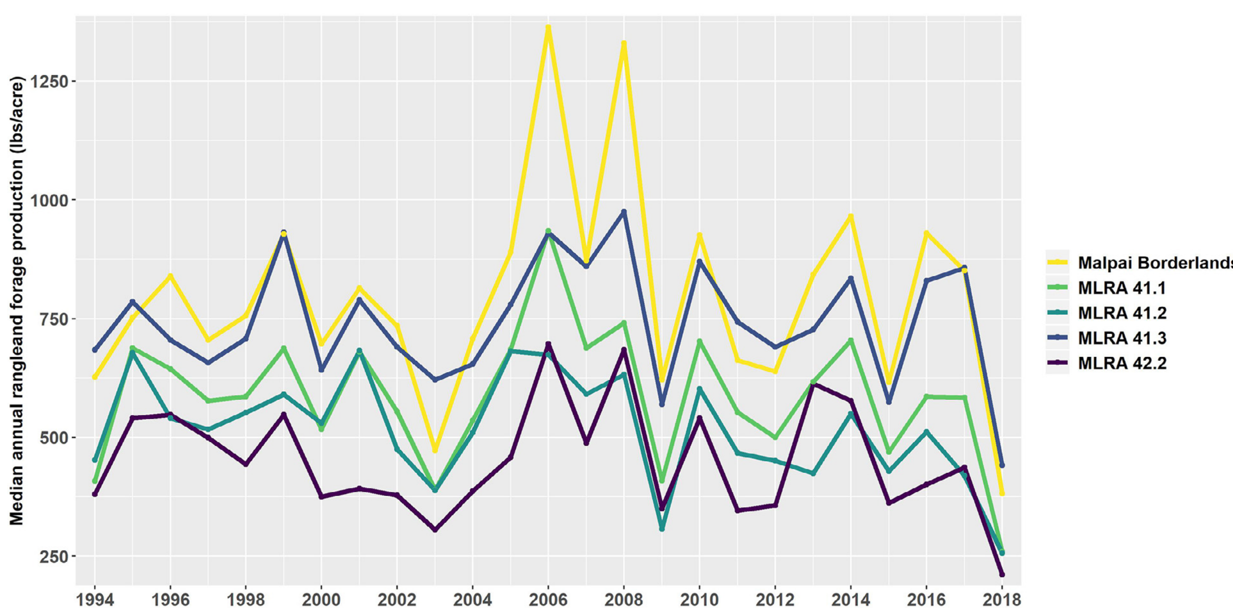

Figure 8. Estimated median annual rangeland production for 250-m pixels occurring in each landscape.

within the MBG compared with surrounding landscapes indicates the effectiveness of conservation easements for preventing change (Rissman and Sayre 2012). On the other hand, the higher rates of rangeland conversion in other landscapes are likely related to the proximity of urban centers and coverage of soils/landforms suitable for cropland. It is important to note that the CDL did not capture land conversion associated with ongoing construction of the Border Wall System along the U.S.-Mexico border. "Border hardening" and associated increases in road networks and water withdrawals in the MBG landscape can conflict with specific biodiversity conservation goals and are largely outside the control of MBG cooperative activities (Sayre and Knight 2010; Peters et al. 2018).

Perhaps the most dramatic result of our analysis is the apparent success of MBG in promoting fire. Outside of the MBG landscape, only a small fraction of landscape area has burned over the 25-yr period examined. Fire density and size are partly a function of fuel availability, which in turn is a function of rangeland production. In this regard, it is useful to compare MBG with MLRA 41.3. The lat-

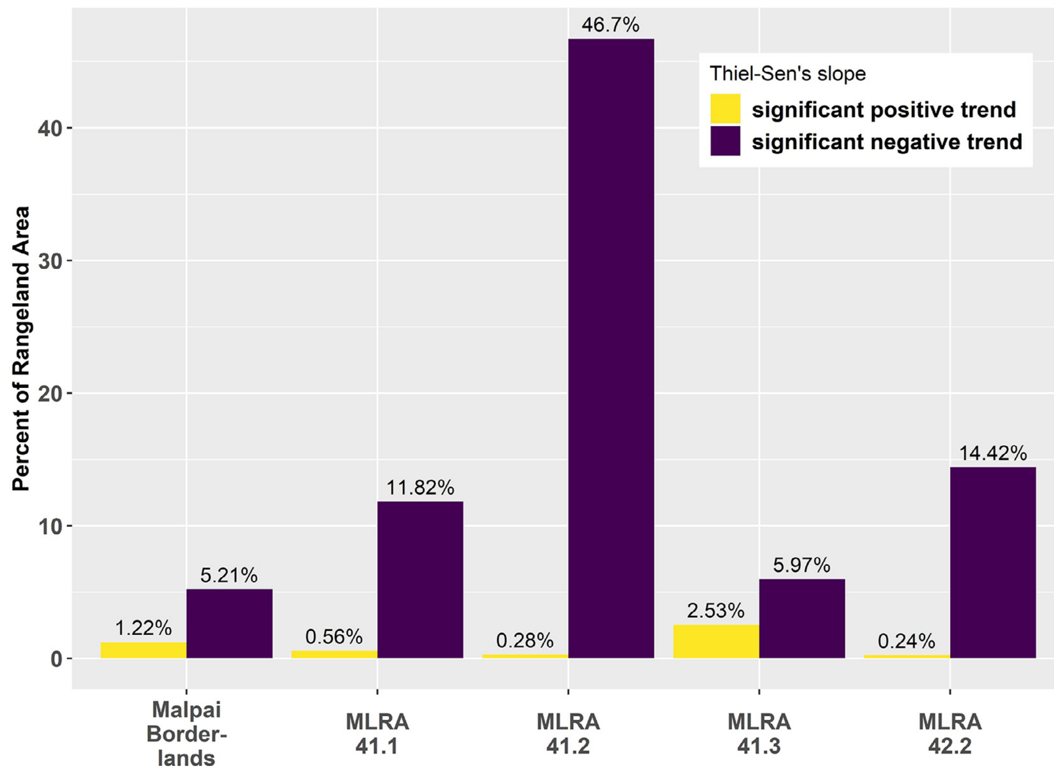

Figure 9. Percent of rangeland area exhibiting significant positive or negative trends in rangeland productivity from 1994 to 2018 in each landscape.

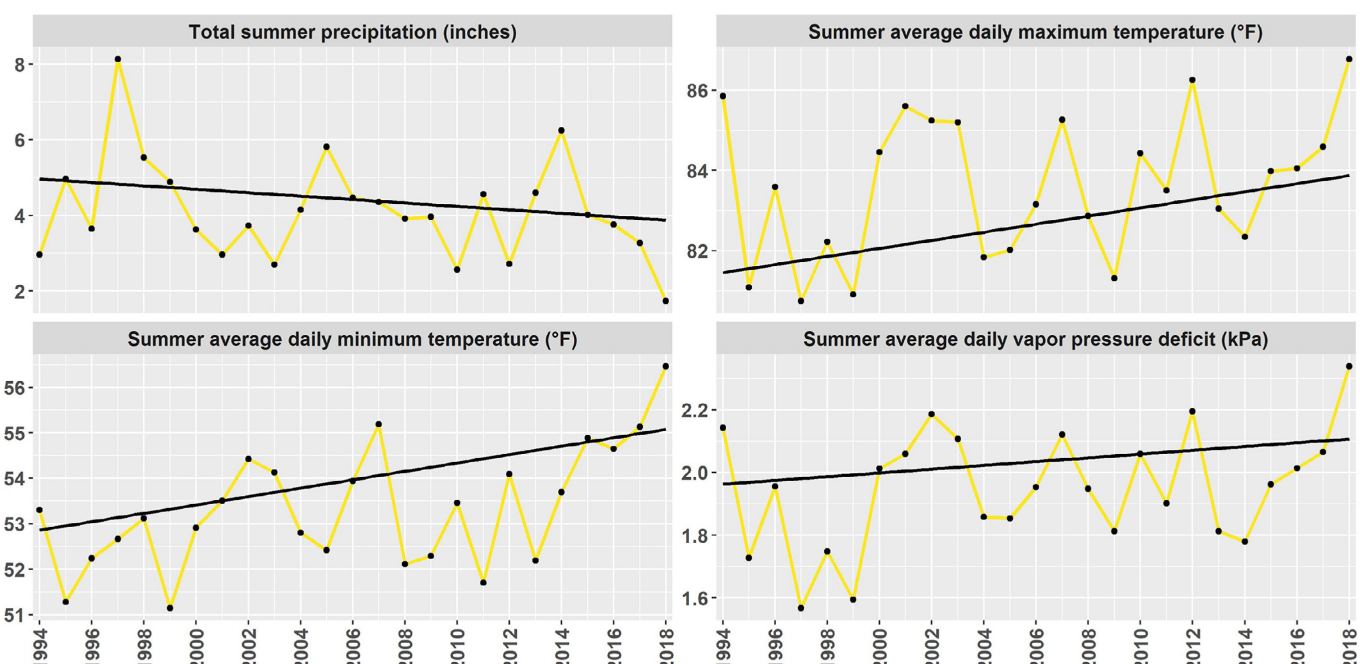

Figure 10. Interannual trends (Sens slope) in select summer growing season (June–September) climate variables from the gridMET dataset for the MBG landscape. Annual values reflect averages for all 4-km^2 pixels.

ter had similar high perennial grass and forb cover and rangeland productivity, yet only a small fraction of the area burned. These differences are likely to be a function of cooperative fire management. Although fire density in MBG was comparable with that of adjacent landscapes (Table 2), some MBG fires were large. These large fires, such as the famed Baker 2 fire, which was among the largest (47 000 acres) successful prescribed fires in US history, were possible only because of intensive coordination among multiple agencies and landowners and because the MBG landscape was relatively unfragmented by urban development (Gottfried et al. 2009). It is also important to recognize that due to the limitations of the fire dataset, some of the burned areas represented by the

MBG may have occurred outside the MBG landscape even though the ignition point occurred within the MBG. This is a good example of how the sustainability goals of the MBG can have an important impact on surrounding areas.

Landscape variation in surface cover and production estimates in the RAP and RPMS datasets (see Figs. 6 and 8) represent cumulative differences in ecological potential (i.e., climate, landscape position, soil fertility, and soil water holding capacity) and management history (McAuliffe 1994; Bestelmeyer et al. 2011). It is currently not possible to fully explain these variations at the landscape level with available data. Nonetheless, we can evaluate differences between landscapes in cover and production considering differences in climate at the same extents using the gridMET data (see Fig. 5). In spite of relatively warm and dry conditions compared with other landscapes, the MBG landscape features relatively low bare ground, high perennial grass/forb cover, and high production. The apparently exceptional rangeland condition of MBG cannot be attributed directly to CAM activities or generally effective rangeland management, but it is consistent with them. High perennial grass/forb cover and warm and dry conditions in the MBG may have also contributed to the high proportion of burned area compared with adjacent landscapes.

Pixel-level trends in cover and production are similarly consistent with relatively favorable rangeland health in the MBG landscape. The percent of rangeland area experiencing significant declines in productivity was lowest in MBG (although similar in MLRA 41.3), and the percent of area exhibiting increasing bare ground was low compared with all landscapes except MLRA 41.3. The percent of area with significant increases in production was small but greatest in MLRA 41.3 and MBG. Again, the spatial extent and pattern of these trends over 25 yr are likely to reflect consistent differences in management (grazing strategies, brush management, fire, and land clearing) and localized variations in climate, landforms, and soils.

The strong aggregation of pixels featuring significant productivity declines in certain areas (see Fig. S1, available online at doi:10.1016/j.rama.2021.03.002) cannot be explained without additional field-based information (e.g., Eddy et al. 2017). Nonetheless, it is encouraging that extensive areas of decline were not detected within the MBG landscape. The minimal area of significant trends in perennial grass/forb and shrub fractional cover in the RAP data require additional investigation. It is possible that significant changes in vegetation have occurred but are concealed by the broad functional group categories. For example, shifts from Prosopis shrub species to subshrubs (e.g., *Gutierrezia sarothrae*), or from forbs to perennial grasses, may have occurred while the cover of their respective RAP functional groups remained stable or fluctuated in response to rainfall (Bai et al. 2004; Gonzalez and Loreau 2009). It is also possible that the estimated cover values in the study region are sufficiently inaccurate from year to year to preclude valid assessments of subtle trends, considering the uncertainty in cover values. At the time of this writing, RAP version 2.0 is available but the source paper is under peer review, so the data were not judged to be ready for use here. Future work will compare ground-based fractional cover estimates not used in model training with RAP 1.0 and 2.0 data. Additional local training data could then be used to improve fractional cover estimates (Allred et al. 2020).

In summary, our findings indicate that MBG is meeting most sustainability goals it established in 1994. Although ranch-based livelihoods have become more challenging (Havstad et al. 2016; Haggerty et al. 2018; Munden-Dixon et al. 2019), the MBG remains a working landscape and ranching continues as properties change hands via intrafamilial and extrafamilial turnover. Fires have occurred over a relatively large fraction of MBG, enabled by an effective system of conservation easements that has prevented development. Although the impact of fire was not detected in shrub fractional cover trends, mean vegetation and bare ground cover estimates suggest a comparatively healthy landscape. Areas of declining production and increasing bare ground may be concerning, but their low occurrence in MBG suggests ecosystem resilience. While we cannot evaluate biodiversity directly, fractional cover proxies suggest comparatively favorable habitat for desert grassland species, following the logic of Muldavin et al. (2001).

Our “big data” comparative approach supplemented with local information on ranch dynamics provided an unprecedented ability to evaluate the effects of CAM, as well as its changing social and environmental context, at a landscape scale. Because most datasets span rangelands of the continental United States, our approach can be broadly applied to inform landscape management. That said, the limitations encountered in our analysis highlight the importance of additional data collection and analysis. First, a comprehensive evaluation of ranch livelihoods would require more detailed interview data to determine economic sustainability and well-being at the family level, as well as the overall socioeconomic health of a broader community (Bentley Brymer et al. 2020). Second, our confidence in vegetation and productivity trends would be increased with independent field validation and local knowledge of the existence and causes of spatial variations in vegetation trends. We propose that rapid, crowd-sourced field evaluations including information on local perceptions of trends and knowledge of long-term management or discrete events (such as a flash drought), using mobile applications such as the Land Potential Knowledge System (Herrick et al. 2017), would provide an ideal complement to remote sensing–based datasets. In addition, recent high-resolution spatial data could be expanded across the region and used to evaluate trends in woody plant cover at broad scales in the Southwest (Ji et al. 2019). Finally, we were unable to locate a suitable standardized dataset to evaluate biodiversity trends (especially threatened and endangered species) in the MBG and surrounding landscapes, which is a common limitation (Jetz et al. 2019). We suggest that structured interviews with wildlife biologists in the United States and adjacent Mexico to collate long-term observations on species of conservation concern might provide useful information for the regional ranching and land management community.

Implications

The use of big data tools supplemented by local knowledge constitutes a novel approach to evaluating long-term, landscape-level sustainability goals linked to CAM (or other) activities. Our application of this approach provides evidence that CAM strategies employed by MBG over the past 25 yr have been effective. Sustaining the effectiveness of CAM in MBG will likely require adaptation to ongoing social and environmental change. Ranch succession is a well-known concern of ranchers throughout the United States (Brunson and Huntsinger 2008; Wilmer and Fernández-Giménez 2015; Munden-Dixon et al. 2019). Trends toward increasing absentee ownership and the immigration of new families are likely to continue. Sustaining essential landscape coordination and knowledge-sharing activities will require new strategies and redoubled effort to engage new local landowners and distant landowners. It will also be important to maintain institutional engagement with turnover in agency staff and participating scientists. Climate change will be an even greater challenge in the years ahead, particularly in this region (Elias et al. 2016; Havstad et al. 2016). Significant increasing minimum summer temperatures over the past 25 yr in the MBG landscape and recent extremes of heat and dryness portend increasingly widespread declines in rangeland productivity and water resources in the region (Gremer et al. 2015; Bradford et al. 2020). Adaptation to these changes, for some producers at least, could be aided by novel beef production systems;

real-time and spatially precise information about livestock, water resources, forage conditions, and climate; and expanded supply chain and marketing information and options (Spiegal et al. 2020). Although there are numerous social, economic, and environmental challenges facing ranchers and other rangeland stakeholders in the years ahead, the integration of CAM with new technologies to support landscape-level monitoring and management will be essential ingredients of sustainability strategies.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This research was supported by appropriated funds to the USDA-ARS Jornada Experimental Range project 3050-11210-009-00D and Jornada Basin Long-Term Ecological Research Program DEB-1832194 and a contribution from the Long-Term Agroecosystem Research (LTAR) network. LTAR is supported by the USDA. We dedicate this paper to the memory of Ben Brown, science coordinator of the Malpai Borderlands Group, who helped put science at the forefront of collaborative management.

Supplementary Materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.rama.2021.03.002.

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