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Social–ecological dynamics of change and restoration attempts in the Chihuahuan Desert grasslands of Janos Biosphere Reserve, Mexico

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Abstract Shrub encroachment and declining grass production are widespread throughout the grasslands and savannas of the Mexico–US borderlands, with negative consequences for ecosystem services, livestock production, and native biodiversity. The problem suggests a complex interaction of social and ecological drivers that are not well understood. Using the Chihuahuan Desert grasslands of the Janos Biosphere Reserve of northern Mexico as a case study, we sought to understand the social–ecological context that shaped landscape change. Our approach included a synthesis of the historical literature and interviews with local residents, with the goal of facilitating long-term grassland restoration. Findings indicate that recent changes in Chihuahuan Desert grasslands are likely related to the co-occurrence of heavy grazing, fire suppression, and the elimination of key species, including prairie dogs and native ungulates. Local residents widely perceive both fire and prairie dogs to be destructive to grasslands and livelihoods. Over the last 50 years, evolving land tenure policies have fragmented the landscape into smaller parcels which typically produce an insufficient livelihood from cattle despite high stocking rates. Declining cattle profitability has motivated the sale and conversion of rangelands to more profitable croplands irrigated with groundwater. Since the founding of the Janos Biosphere Reserve in 2009, universities, local cattle operators, conservation organizations, and federal agencies have begun collaborating on restoration activities. While complete restoration of grasslands is unlikely, progress appears possible largely because of the willingness of local residents to try new management practices that may improve their ability to benefit from the land.

Keywords Land use change · Shrub encroachment · Ejido · Grazing · Restoration · Mexico

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Introduction

In Mexico, agriculture and cattle grazing operations contributed to more than 75% of recent land use change, followed by deforestation and urbanization (SEMARNAT 2003). Conversion of grassland to cropland represents the most recent and most obvious type of land cover change within the Janos Biosphere Reserve (JBR) of northwestern Chihuahua, Mexico (Ceballos et al. 2010; List et al. 2010; SEMARNAT 2013). Over the last century, the Janos region has experienced widespread decline of numerous bird species, burrowing rodents, and an entire suite of herbaceous vegetation. At the same time, there has been a dramatic increase in shrub cover, particularly honey mesquite (*Prosopis glandulosa* Torr.) (Ceballos et al. 2010; List et al. 2010; SEMARNAT 2013). Rangeland restoration is being implemented to combat shrub encroachment and biodiversity loss, but the transition from rangeland to irrigated crops is unlikely to be reversed.

The ecological changes on the JBR are not unique to northwestern Chihuahua, but are representative of changes documented throughout extensive areas of the Mexico–US borderlands (hereafter, Borderlands), including grasslands of the Sonoran and Chihuahuan Deserts, (Van Auken 2000; Grover and Musick 1990) and the Tamaulipan Biotic Province of southern Texas (Archer et al. 1988). More than 50 years of research devoted to the ecology of shrub encroachment throughout the Borderlands has provided many insights but few conclusive answers as to the primary drivers of encroachment. However, the vast majority of research devoted to compositional and functional changes of grasslands has focused on ecological processes while largely ignoring the social history of land management. Credible links between social and ecological processes are limited, though a new focus on social–ecological systems research may improve our understanding of how social and political (policy) factors influence ecosystems (e.g., Huber-Sannwald et al. 2012). A lack of understanding of the social processes that have facilitated grassland transitions hinders effective mitigation of existing land use patterns needed for successful restoration. Past management activities have led to localized species loss and undesirable vegetation transitions (e.g., declining perennial grasses, increasing shrubs) that some landowners, organizations, and agencies want to reverse. Restoration success is limited, however, by ecological barriers, such as loss of topsoil, and by social constraints, such as the economic needs of landowners.

We present the JBR as a case study that highlights the complicated social context of what must be seen as a social–ecological problem that extends throughout multiple ecoregions in the Borderlands and beyond. To that end, we draw on extensive ecological research as well as formal interviews, participant observation, and textual sources to present both the ecological and social history of the JBR. We describe the current collaborative restoration activities on the JBR that balance conservation objectives with the (varied) profit-seeking management goals of landowners. We conclude by summarizing social and ecological hurdles to restoration and recommend a potential strategy for how to proceed.

Ecological context: shrub encroachment in the borderlands

Despite ostensibly conclusive definitions by the United Nations Convention to Combat Desertification, the precise meaning of the terms “desertification” and “degradation” remain contested (Stiles 1995; Huntsinger 2016), and there are accusations that these terms are more often used to advance political agendas than to describe actual environmental processes (e.g., Olsson 1993; Andersson et al. 2011). For the purposes of this article, we use the term degradation to refer to multiple factors with negative effects on native ecosystems occurring simultaneously within the study area of Chihuahuan Desert grassland and other regions of the Borderlands: increasing shrub cover, declining grass production, transition from perennial grasses to annual grasses, and decreasing biodiversity. These changes imply loss of numerous ecosystem services (Archer and Predick 2014; Turnbull et al. 2014) as well as declining economic returns for cattle raising, the region’s dominant land use.

In the southwestern US, mesquite (*Prosopis* spp.) now dominates 38 million hectares and creosote bush (*Larrea tridentata* Cov.) an additional 19 million hectares, a large portion of which was semiarid southwestern grassland until at least the late 1800s (Van Auken 2000). Stable carbon isotope studies have confirmed the relatively recent takeover of C_4 grasslands by woody vegetation in southeastern Arizona (McPherson et al. 1993) and southern Texas (Boutton et al. 1993). Longer term ecological records indicate that much of the Borderlands shifted back and forth between grass-dominated and shrub-dominated states since the Holocene, depending on multi-century climatic patterns (Turnbull et al. 2014). On the Jornada

Experimental Range of south-central New Mexico, an area ecologically similar to the JBR, honey mesquite was the primary dominant on 16% of the land in 1916 but increased to 59% cover by 1998 (Gibbens et al. 2005).

There is little certainty in what causes shrub encroachment, and the relative effects of the multiple drivers vary between sites (Archer et al. 1995). In general, four possible principal causes are put forward: altered rainfall patterns, increased atmospheric CO_2 concentrations, reduced fire frequency, and altered herbivory pressure (Archer et al. 1995; Van Auken 2000; D'Odorico et al. 2012). Increased seed dispersal by livestock may also play a role (Van Auken 2000; Gibbens et al. 2005; Fredrickson et al. 2006), as might eradication of prairie dogs and other rodents (Weltzin et al. 1997). Climate change and increased CO_2 concentrations are more likely facilitative than causative, as the timing and geographical extent of shrub encroachment at sites around the world rarely correlate with climatic variables (Archer et al. 1995). Increased grazing by livestock, often in conjunction with decreasing fire frequency, is most often thought to be the primary driver of shrub encroachment, particularly in the Borderlands (Buffington and Herbel 1965; York and Dick-Peddie 1969; Grover and Musick 1990; Gibbens et al. 2005; Yanoff and Muldavin 2008).

Grazing and shrub encroachment reduce fine fuels that carry fires across a landscape, thus lowering the frequency of fires that might otherwise suppress woody vegetation. As shrubs have become increasingly dominant over the twentieth century, the associated reductions of fine fuels together with active fire suppression have diminished the size, frequency, and intensity of fires (Ervin et al. 1959; Wright 1980; Drewa et al. 2001; Luna 2009). These changes have overridden the synchrony of periodic droughts and fire (Swetnam et al. 2001; Kitzberger et al. 2007), creating a feedback loop that further facilitates shrub encroachment (Scifres 1980; Archer et al. 1995; Smeins et al. 2005). Despite this general trend, fire is not typically considered to be the primary control on shrub encroachment in the Borderlands (Branscomb 1958; York and Dick-Peddie 1969; McPherson 1995). While fire may consume above-ground growth of mesquite, the plants are rarely killed and tend to regenerate quickly (Martin and Cable 1973; Wright et al. 1976; Hanselka et al. 2007; Killgore et al. 2009).

Some authors have suggested that shrub encroachment has been spurred by the combination of heavy grazing and specific climatic conditions—especially drought—that have hindered the regrowth of bunchgrasses (Grover and Musick 1990; Kizos et al. 2014). It is further possible that the grass dominance recorded in the nineteenth century was the product of a 300-year weather pattern (the 'Little Ice Age') which has since ended, and that shrubs are now favored by the current climate (Neilson 1986). Other possible contributing factors include widespread eradication campaigns of prairie dogs (*Cynomys* spp.), which have been shown to limit shrub growth (Weltzin et al. 1997; Ponce-Guevara et al. 2016), and the reduced population and extent of indigenous communities that practiced extensive harvesting of mesquite beans (Fredrickson et al. 2006).

Methods

Site description

The JBR has been described as a hotspot for wildlife diversity and until 2005 was home to the largest remaining black-tailed prairie dog (*Cynomys ludovicianus*) complex in North America (Ceballos et al. 2010). Humans have been a part of the Janos region for at least 12,000 years (Hard and Roney 2005), but few population centers existed in the region until the 1960s (Ceballos et al. 2005a; Hard and Roney 2005). The 526,091 ha JBR is located in northwestern Chihuahua, and is primarily composed of basin-and-range country on the edge of the Chihuahuan Desert, with a matrix of soil types ranging from loamy and clayey sites to more gravelly piedmont slopes (Davidson et al. 2010) (Fig. 1). While the southern and western edges of the JBR include forested sections of the Sierra Madre Occidental, this study focuses on the northern half, which is principally desert grassland with an elevation of approximately 1400 m. Mean annual precipitation is 306 mm but is highly variable, with most occurring during the summer monsoon from July through mid-September. Temperatures range from a minimum of −15 °C in winter to a maximum 50 °C in summer, with an annual mean of 15.7 °C (Davidson et al. 2010).

Today, the vast majority of the JBR is composed of private ranches, followed by *ejidos* (government-created agricultural communities, described below)

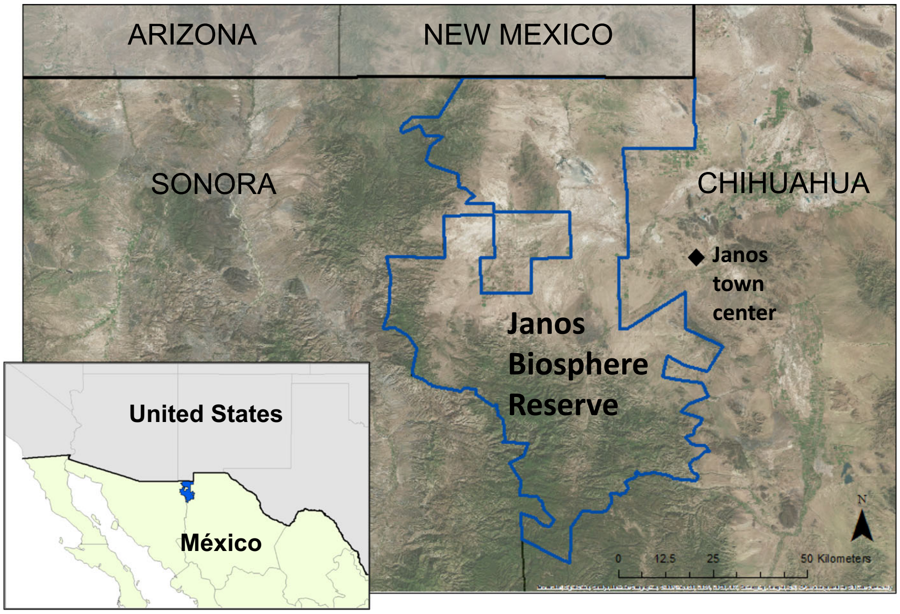

Fig. 1 Location of Janos Biosphere Reserve (JBR), in Chihuahua, Mexico. The southern and eastern portions of the JBR include forested sections of the Sierra Madre Occidental, while the remainder is primarily desert grassland. The apparent hollow center of the JBR is to exclude a Mennonite farming community Map by T. Hruska; *Sources* ESRI

and Mennonite agricultural colonies (Ceballos et al. 2005a; List et al. 2010). The JBR lies almost entirely within Janos municipality, which had a population of 10,214 inhabitants in 2000 (INEGI 2000). Only a relatively small portion of this population resides within the JBR, as the town center lies outside the eastern boundary (Ceballos et al. 2005a; List et al. 2010).

Data sources and research methods

Data presented in this paper come from multiple sources. The ecology of the JBR is largely a synthesis of research conducted over the last thirty years primarily by researchers affiliated with the Universidad Nacional Autónoma de México (UNAM). The social history is drawn partly from textual sources, including data from the 1994–2009 censuses and from Mexican government agencies (e.g., SEMARNAT 2003), and partly from formal interviews and informal discussions with local residents. This type of qualitative research is necessary for understanding decision-making processes that lead to degradation or restoration of rangelands (Sayre 2004).

In July and August of 2010, we interviewed 25 key informants including 2 Mennonites, 3 ranchers, and 20 *ejidatarios* (*ejido* members), using a semi-structured interview protocol. The three groups lived on the JBR for an average of 37.5 (Mennonite), 42 (rancher), and 47 (*ejidatario*) years. Of the *ejidatarios*, eight identified their occupation as farmers, seven as ranchers, three as cowboys, one laborer, and one grocery store owner. The initial interviewee cohort of elders and town settlers was selected to provide historical context to the current state of the JBR social–ecological system. Additional informants were identified using a snowball network sampling approach (Bernard 2006). Key themes of inquiry included grazing, land cover change, climate change, social capital and collective action, and use of fire. Interviews were recorded in Spanish and fully transcribed. After transcription, interviews were thematically coded using Atlas TI (Atlas TI Scientific Software Development 2011). Quotes used in this paper were translated to English by D. Toledo. The data presented were made anonymous to protect confidentiality.

History of land use

In the late nineteen century, President Porfirio Díaz's government expropriated vast amounts of land from smallholders in northern Mexico for sale to US and

Mexican interests in timber, cattle, mining, roads, and railroads (Hart 2006; Dale-Lloyd 1987). The area now composing the JBR was then largely within two vast US-owned corporate ranches, Las Palomas Land and Cattle Co. and Corralitos Land and Cattle Co., which together covered more than 1.37 million hectares (Hart 2006). Cattle production surged under new ownership, overwhelmingly destined for export to the US, which has remained the primary destination for Chihuahuan cattle ever since (Machado 1981; Pérez-Martinez 1993).

Following the Mexican Revolution (1910–1920), Article 27 of the Constitution enabled the government to expropriate large private land holdings for redistribution to landless peasants in the form of *ejidos*, collectively managed agricultural communities without private land titles (Cornelius and Myhre 1998; Assies 2008). More than half of Mexico's arable land was in *ejidos* by 1990 (Cornelius and Myhre 1998), but relatively little in the arid north. Between 1965 and 1975, seven *ejidos* were established on what is now the JBR, and many ranches were subdivided among family members or sold off. Mennonite farmers, who had immigrated to Mexico in the 1940s, bought some of this land to form three new colonies outside of Janos devoted to low-technology farming and dairying (Bridgemon 2012; Interviews).

Following structural adjustment and other economic reforms in the 1980s, a constitutional amendment in 1992 allowed privatization of *ejido* land and the subsequent private sale or rental of individual parcels (Cornelius and Myhre 1998). Shortly thereafter, the three Mennonite colonies near Janos dropped their previous limitations on technology and finance (Sawatzky 1971; Interviews) and began using bank loans to purchase farm machinery and install groundwater irrigation systems. The new technology allowed for an expansion of cash crop production, incentivizing Mennonites to purchase newly privatized *ejido* grazing land for conversion to irrigated agriculture (Fig. 2).

From 1993 to 2008, irrigated agriculture in the Janos area increased from 731 to 12,845 ha (Ceballos et al. 2010), causing the water table to drop 10–30 m from 1988 to 2015 (Diario Oficial de la Federacion 2015). Across Chihuahua, irrigated agriculture expanded 44% between 1980 and 2001, increasing irrigation use by 75% (Rosson et al. 2003), in part stimulated by the deregulation of irrigation systems (Whiteford et al. 1998). Government programs like the 1994 program of direct rural support (PROCAMPO) not only helped feed poor farmers of staple crops (Rubio 2003; Assies 2008) but also subsidized the expansion of large-scale agriculture (Field notes 7/14/2010).

In December 2009, the Mexican federal government established the JBR with two goals: (1) to maintain biological diversity and ecosystem function and (2) to promote a model of economic development that would raise the quality of life of local residents (Ceballos et al. 2005a; List et al. 2010). Biosphere Reserve status in Mexico limits but does not preclude human use, and on the JBR the primary goals were to halt the conversion of rangeland to crop agriculture and restrict groundwater withdrawals.

Results

Interviews confirmed that the Janos area has been subject to deep social, political, and economic changes that significantly interacted with and contributed to ecological transitions. While residents are well aware of the grassland degradation, the perceived causes often differed from those proposed by researchers. Below we explore some of the social–ecological changes reported by interviewees (for selected tabularized results, see Table 1).

Shrub encroachment

Mesquite now dominates what were once grassland ecosystems with scattered shrubs. Elders who grew up in this region reported that, in their youth, mesquite was either absent or only in scattered patches with large tree-like shrubs. Several of our respondents claimed to have planted mesquite in their yards so they could eat the beans, and one old *ejidatario* and one old rancher who grew up in the region said that mesquite was spread across many of the rangelands by livestock, including burros. As one *ejidatario* stated: "I remember that we did not have mesquite here in San Pedro but when the miners began bringing water for the mines using burros, the places where the burros traveled and rested were the areas where mesquite would be born." Of the post-1970 arrivals to the area, all reported that mesquite was present throughout the area when they arrived.

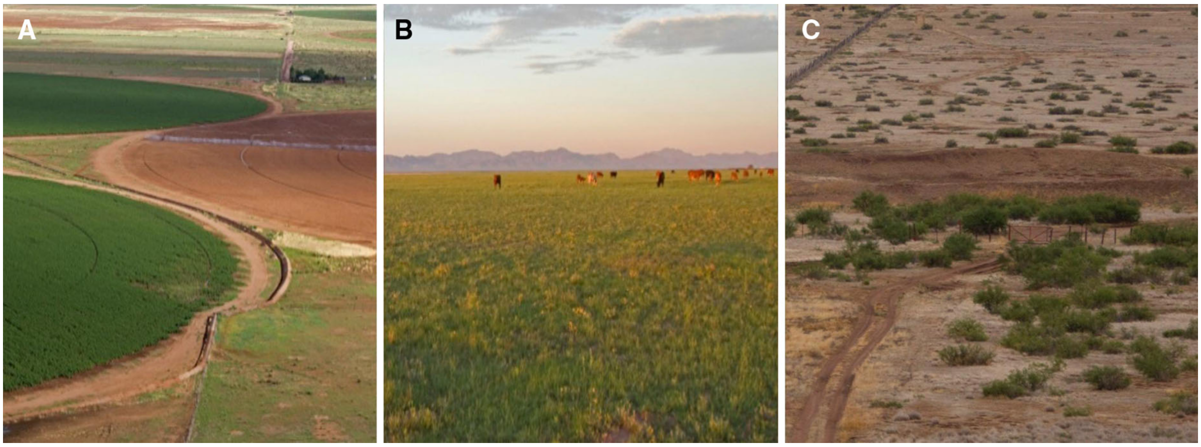

Fig. 2 Land change within the Janos Biosphere Reserve can be mostly attributed to **a** conversion of desert grasslands to irrigated agriculture (**A**); heavy grazing (**B**); and shrub encroachment (**C**) *Photos* D. Toledo

Table 1 Percentages of interviewees who agreed with the given statement or performed the given action

Opinions held or actions taken by the interviewee	Ejidatario ($n = 20$) (%)	Rancher ($n = 3$) (%)	Mennonite ($n = 2$) (%)
Stocking rates have affected grassland condition in the land they use	75	0	N/A
Drought has influenced crop and/or forage growth	80	66	100
Expanding shrub cover has affected grassland condition	60	33	50
Prairie dog numbers have declined	50	66	100
Fire use can be beneficial for grassland systems	20	0	0
Have converted rangeland to cropland	25	33	100

Due to the sampling method employed, the percentages cannot be extrapolated out to the rest of the population

Many people classified mesquite into two types based on growth form. We heard from four different interviewees that mesquite eradication treatments only result in shorter mesquite plants that spread and occupy more space than the original, more tree-like, mesquite plants. As one of the older *ejidatarios* stated: "Mesquite spread slowly and based on drought. There is a very bad type of mesquite. The small one just uses up land. The tall one is better. The small one is very bad."

Overgrazing versus drought

Interviewees have experienced ecosystem changes first hand and attribute grassland degradation primarily to drought rather than seeing drought and livestock management as having additive effects, evidenced by the rancher who told us: "I do not overstock my land, it just hasn't rained so I do not have enough grass for my cattle." This rancher based stocking rates on factors other than existing forage production, and believed that lack of rain was insufficient reason to destock. He similarly dismissed the notion that consistent overstocking could cause lasting damage. The notion that ecosystem changes were due to climatic changes and were mostly independent of management resonated throughout many of the interviews.

According to interviews, the JBR has recently gone through cycles of severe drought accompanied by grass and animal mortality and periods of very wet years that have helped regenerate productivity of some grasslands, while other areas have remained in a degraded state or even worsened. When wet periods allowed for initial recovery, increasing livestock numbers often prevented grasslands from fully recovering. This was evident during the late 1970s and early

1980s, when cattle numbers remained high, while the condition of grasslands deteriorated. As one *ejidatario* put it: “When we get rain, weeds come up and they [other *ejidatarios*] start bringing in even more animals. Our grazing land is so small that so many animals just begin to dig into our soil and it just starts to get more and more dug up.”

Changing land tenure

Starting in 1992, *ejido* parcels could be legally privatized, subdivided, sold, and/or be used as collateral for obtaining credit (Registro Agrario Nacional 1998; Assies 2008). Faced with the opportunity to receive a lump sum of money, many *ejidatarios* took it: “We first got the Agrarian certificates and then they gave us the titles for our land. When we got the titles, many of us sold our land.” Due to the low profit-per-hectare rate of raising livestock, buyers of privatized *ejido* parcels have generally been Mennonites who could afford to convert the land to irrigated agriculture.

At the regional scale, the fragmentation of large land parcels meant that more people were dependent on less land for their income, incentivizing higher stocking rates in the short term and making destocking during drought economically unviable. As one Mennonite elder described:

> The plains looked very different [before the *ejidos* were founded] because there were a lot less cattle. I think the land belonged to Carlos Villareal… He kept very few cattle, about 1 cow per 17 hectares, and always kept really good grass. He had thousands of hectares so he had no problem. But when the *ejidos* were formed everyone was working for themselves and instead there were about 17 cows per hectare [he said jokingly]. The ranch started getting too small for that amount of cattle. That was the problem. They ate all the grass and now there are only weeds.

Similar sentiments were expressed by other interviewees, including two older *ejidatarios* who lived in the area before the *ejidos* were founded. They thought that some of the larger ranches that had escaped government expropriation were eventually divided among family members either to keep the properties below newly set parcel size maximums or simply to provide for multiple heirs.

Social capital

In the JBR, trust, reciprocity, and collective action have declined since the inception of the *ejidos* in the 1960s. Several of the *ejidos* were founded as a result of collective land occupations, and all of our respondents who were present at that time told us about how they all worked together to get the *ejidos* implemented and then worked together on land improvements. Over time, cooperation faded. As one *ejidatario* told us:

> The government sent us some equipment so that we could clean up the fields and build some water wells and we built about 30 wells. Then the government asked us to be part of a larger cooperative but those of us who had actually worked to get the wells done did not want to join. With time you discover things like who works and who does not. I am not going to work so that others do not have to work.

Most *ejidos* now operate with a form of semi-formal private grazing rights, where *ejidatarios* who do not want to manage livestock rent or sell the right to graze the government-set number of cows per household (established when the *ejidos* were founded) to other *ejidatarios*. This practice has helped insure that more cattle are owned by people who are interested in managing them, but has also given a smaller number of people greater control over the fate of *ejido* rangelands.

The Mennonite community has reportedly been able to maintain community cohesion, enabling them to take advantage of the land tenure restructuring by using large bank loans to buy land and sink wells within what is now the JBR. Such loans are beyond the reach of *ejidatarios*, who lack collateral, and even some ranchers, who may already carry large debts. While biosphere reserve policy forbids conversion of rangeland to cropland, Mennonites have continued to purchase and convert rangeland within the JBR.

Perceptions of prescribed fire

Prescribed fire may be used as a cost-effective shrub management option, yet this practice is not widespread on the JBR (Luna 2009). With few exceptions, our interviewees thought that fires can be harmful for economically important species and that igniting fires is too risky. This may be attributable in part to the fact that most interviewees grew up in other parts of the country where burning may not be common or beneficial, but interviewees also referenced laws and policies aimed at preventing and combating fire. In general, interviewees did not consider fire to be a natural disturbance in this ecosystem. Furthermore, few interviewees had land they could move their livestock to during and following a burn, making the temporary loss of forage logistically prohibitive. Offering a minority perspective, one *ejidatario* stated, "There used to be fires and the grasses would come back nicer…but people do not burn anymore because these people do not know anything about that."

Discussion

Grassland degradation

Concurring with regional academic assessments, residents reported that the JBR currently produces more shrubs and less grass than in past decades. Long-time residents' accounts of the region as being essentially mesquite-free within living memory are surprising given histories elsewhere (e.g., Gibbens et al. 2005). Such a start date suggests that mesquite encroachment was initiated by a driver other than grazing, at least of the type practiced for more than 50 years by large ranches in the late 1800s and early 1900s. Confirmation would require more complete ecological records.

The best record available is the dissertation research by Donald Brand in 1929–1933. Brand (1933) described a mixed shrub-grass landscape, with mesquite more abundant in the valleys and washes, in fine-textured soils, and areas with high water tables, while creosote dominated on upper slopes and benches. Grasses were "well developed throughout" the plains, "frequently forming a near continuous cover on the piedmont slopes and in the broad shallow draws." Brand reported these grasslands to be composed primarily of perennial grasses: gramas (*Bouteloua* spp.), various needlegrasses (*Aristida* spp.), curly mesquite (*Hilaria belangeri* Steud.), tobosa (*Pleuraphis mutica* Buckley), several species of *Sporobolus*, and false buffalo grass (*Monroa squarrosa* Torr.). Brand's description in 1933 was of a heterogeneous landscape whose relative composition of grasses and shrubs varied with topoedaphic and climatic characteristics. That basic description still applies, making it difficult to know the degree of change (Figs. 3, 4), though the significant cover of annual grasses in heavily grazed areas described by interviewees and observable today has not been documented previously. Grazing-induced conversion from perennial to annual grass dominance has been documented elsewhere, though less conclusively in arid lands (Díaz et al. 2007).

Recent estimates of land cover for the JBR put shrub cover at 16% and grassland at 34% (Ceballos et al. 2005b). Bare ground within grasslands expanded from 6645 to 52,123 ha between 1990 and 2000 (Ceballos et al. 2010), though it should be noted that the years 1993–2003 made up the worst drought in 50 years (Ortega-Ochoa et al. 2008). Highly variable rainfall and droughts, such as that from 1993 to 2003, may mask or override the effects of grazing on vegetation composition as asserted by interviewees, though proof is lacking. The annual grassland, dominated by *Aristida adscensionis* L. and *Bouteloua barbata* Lag., is thought to be promoted by heavy livestock grazing and potentially by prairie dogs, who primarily occupy shortgrass and annual grasslands (Ceballos et al. 2005b). Cattle disproportionately graze the edges of prairie dog colonies (Sierra-Corona et al. 2015), and it is possible that grazing pressure has caused a transition in some long-standing prairie dog colonies from shortgrass to annual dominance. Limited research suggests that some perennial grasses of the Borderlands' desert grasslands are sensitive to heavy grazing, and that perennial grass cover declines when herbivores consume more than 40% of annual standing forage (Martin and Cable 1973; Holechek et al. 1999). Interviewees reported increased grazing pressure in recent decades, and no interviewees reported destocking during dry years, in part due to the belief that grazing pressure does not affect long-term ecology. Attempts to change this pattern would have to contend with household economics that depend on every possible cow.

Interviewees claimed that prairie dogs harm grasslands and reduce cattle production, and extermination has long been a common practice. Long-term (25 years) prairie dog monitoring documented extensive population declines as well as vegetation changes following the extirpation of specific colonies. Early

Fig. 3 View across Heurigo Valley toward Sierra de Enmedio from Sierra Espeulas. Note increased shrub cover Top photo taken c. 1931 (Brand 1933), bottom photo in 2013 (R. Sierra-Corona)

survey work in 1988 estimated that prairie dog towns occupied an area of 55,258 ha (Ceballos et al. 1993). By 2005, the complex had declined in area by 73%, to around 15,000 ha, with about half of the loss directly caused by expanding crop agriculture (Ceballos et al. 2005a, 2010). The poisoning of the 1588 ha Los Ratones colony in 1988–1990 resulted in 16% of the area becoming invaded by mesquite and 20% by ephedra/Mormon tea (*Ephedra trifuca* Torr.) by 2006 (Ceballos et al. 2010). This response matches that from manipulative experiments using prairie dog exclosures on the JBR (Ponce-Guevara et al. 2016) and elsewhere (Weltzin et al. 1997). Given the experimental evidence and the correlation of shrub expansion with prairie dog declines, it appears likely that prairie dogs are beneficial for long-term grassland maintenance and thus to cattle production, despite local opinion. The role of both prairie dogs and heavy grazing in the conversion from perennial to annual grass dominance deserves further study.

Prescribed burning is often used (where legally permitted) to control shrubs but appears to have

Fig. 4 View northwest across Ojitos and the Carretas plains. Note that woody cover has formed denser thickets of lower-statured plants Top photo taken c. 1931 (Brand 1933), bottom photo in 2013 (R. Sierra-Corona)

negative consequences for important perennial grass species under certain, still unknown conditions (Martin and Cable 1973; Drewa and Havstad 2001; Killgore et al. 2009). It is thus difficult to say how misplaced the assertions of interviewees were claiming that fire damages local grasslands. Even if fire is conclusively proven to benefit grassland health in this system, challenges associated with lack of fine fuels (dry grass material) required to carry a fire and the need for corresponding and coordinated cattle relocation remain to be addressed.

Grassland restoration

Walker and Salt (2012) claimed that improvement of degraded social–ecological systems requires acknowledgement of the current degraded state, willingness to change, and having the capacity to change. Our interviews revealed that people have noticed social and ecological changes in the region, and although there is a sense of defeat, recent projects have shown that many JBR residents are willing to try new practices that might improve grass and cattle production in the long run.

That said, the degradation observed in the JBR fits a broader pattern of grassland-to-shrubland transition that is widely believed to be irreversible on a human timescale (Archer and Stokes 2000; Gibbens et al. 2005; Turnbull et al. 2014). Mesquite removal has been attempted throughout the Borderlands for decades, including on over 34,000 ha of private land in the Altar Valley of southern Arizona from 1950 to 1980 (Sayre 2007). Mesquite removal can stimulate a rapid increase in herbaceous forage production if followed by sufficient rain (Martin and Cable 1973), but in general has proven rarely economical and almost always temporary (Archer and Predick 2014). Removing grazing does not by itself reverse shrub encroachment and can actually exacerbate it (Archer and Stokes 2000; Browning and Archer 2011).

Numerous restoration efforts are currently underway using Mexican federal CONANP (National Commission of Natural Protected Areas) grants and private funds (e.g., Alianza, WWF-FCS), and implemented by the Universidad Autónoma de Nuevo León, IMC Vida Silvestre A.C., and Instituto de Ecologia UNAM. Tactics are varied and dependent on what local partners are willing to try. Many practices are still in the trial phase (e.g., soil restoration via air roller, contour and key lines, and yeoman's plow), to be expanded pending results. Shrubs are being mechanically removed to halt expansion and to provide firewood for *ejidatario* partners, though this by itself is not seen as a long-term solution. Thirty-five ha of native perennial grass were grown under irrigation for seed collection in fall 2016 and subsequent sowing in areas of mesquite removal. Construction of gabions has begun on partnering *ejidos* and ranches to halt gully formation along ephemeral streams and potentially increase soil moisture to benefit herbaceous productivity.

Project partners started a sustainable cattle ranching program in 2011 with the aim of learning and teaching improved cattle ranching techniques. One grazing group, on Ejido San Pedro, is operational and instrumental in many restoration project trials; more such groups are expected to start soon, and many private ranchers are already collaborating as individuals. To date, there have been workshops on stockmanship, low-stress livestock management, rotational grazing, cattle reproductive health and nutrition, soil restoration, human nutrition, and backyard gardening. Similar workshops may be able to alter the conception, espoused in many interviews, that livestock management practices have little effect on grassland health, and may also develop management practices that better maintain perennial grasslands.

Moving forward, persistent challenges

Shrub encroachment and conversion of land to agriculture are the most persistent challenges to maintenance of biodiversity and ecosystem services in the JBR. Restoration efforts are and will be stymied by the common conceptions of fire, prairie dogs, and the effect of heavy grazing. The need for cattle income encourages consistently high stocking rates, and shrub encroachment exacerbates this by reducing the available forage per hectare. Restoring diverse grassland communities where they have been lost must by necessity be opportunistic and flexible in approach, with practices matched to ecological conditions and landowner willingness to participate. Trials are needed to learn how multiple management practices might be combined, such as mechanical mesquite removal paired with successive fires and the addition of ungulate browsers. Finding willing landowners to partner on these trials requires ongoing community outreach and identifying where common goals can be met.

Economics pose another challenge to restoration, beyond mere funding shortfalls. Conversion of rangeland to irrigated crop agriculture is the biggest threat to biodiversity on the JBR, and is driven largely by the fact that irrigated crops are far more profitable per hectare than grazing cattle. As palatable grass production declines, crop production becomes increasingly favorable economically. Land conversion will continue to be a profitable threat to grassland biodiversity as long as groundwater can be accessed for irrigation. Conservationists and restoration practitioners could improve the likelihood of maintaining rangeland biodiversity through collaborations with livestock producers that implement restoration activities on private rangelands while working to increase the profitability of sustainable livestock production as an alternative to land conversion.

Conclusions

Livestock grazing, together with other land management practices such as fire suppression and prairie dog extermination, likely played a crucial role in shrub encroachment in the Borderlands (Buffington and Herbel 1965; York and Dick-Peddie 1969; Grover and Musick 1990; Gibbens et al. 2005; Yanoff and Muldavin 2008). The practices that contributed to grassland degradation on the JBR were part of a specific historic social context that was revealed through interviews with local residents. For example, it is clear that both prairie dogs and prescribed fires have been largely removed from the landscape because of the perceived damage to grasslands and reduced cattle profits. Changing land tenure patterns not only increased grazing pressure on the landscape, but also made converting rangeland to irrigated crops a profitable strategy for those with sufficient access to capital. Ecological restoration efforts must now address those social drivers of degradation in order to achieve durable improvements in the land (Huber-Sannwald et al. 2012).

Restoration efforts are hindered by some forces beyond control, such as climate change and low international beef prices. While the JBR is protected by legal policy, declining cattle profitability in the Borderlands raises the threat of further conversion of rangeland to alternate vegetation types and land uses (Sayre et al. 2013). The collaborative restoration activities implemented to date are being supported by a two-pronged research approach: ecological research to understand how shrub encroachment can be suppressed, and social research to understand the social drivers of degradation and to develop improved land management practices that can be sustained long-term. Based on our findings, we recommend this approach for other areas with pervasive restoration challenges.

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