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Grassland–shrubland transformation and grazing: A century-scale view of a northern Chihuahuan Desert grassland

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ABSTRACT

We assessed vegetation change from the 1800s to late 1900s in a Chihuahuan Desert grassland and examined grazing effects. The study area was grazed until 1943 when livestock were removed from a portion. This enabled us to examine shrubland invasion in a historical grassland, relative to continuous grazing and exclusion. Shrublands invaded most of (87%) the sample units, 66% became at least half shrubland, and mean grassland patch size fell 90%. Shrublands invaded more sample units in the grazed site than exclosure (94% vs. 80%), and 22% more grazed site units were very highly invaded (at least 95% shrubland). Grazed site patch size decline was higher, on average, than exclosure patch decline. Results corroborate regional grassland loss and forewarn remaining study area grasslands may be at risk. The increase in shrublands following historical grazing and higher invasion in the grazed site suggests grazing effects. However, widespread shrublands across the study area tempered conclusions. Study limitations included information gaps, challenges detecting multiple variables and impediments to statistical analysis, given inherited historical conditions. We delimited areas with restoration potential based on spatial analysis, and discussed management response when grazing effects are obscured by a lack of details about the past.

1. Introduction

Semiarid grasslands have decreased dramatically and undergone substantial invasion by woody plants within the past one and one half centuries across the globe (Niemeijer et al., 2005; Van Auken, 2000) and in the northern Chihuahuan Desert (Desmond and Montoya, 2006; Gibbens et al., 2005; York and Dick-Peddie, 1969). Explanations include climate variation, livestock overgrazing, altered fire regimes, small herbivore impacts, desertification and cross-scale ecological dynamics (Betancourt, 1996; Brown et al., 2001; Grover and Musick, 1990; Humphrey, 1958; Peters et al., 2006; Schlesinger et al., 1990). Exact causes of grassland decline are difficult to pinpoint, however, because of complex interactions and variable effects among contributing factors (Milchunas and Lauenroth, 1993). Empirical studies that target particular mechanisms are rare since historical conditions are not well documented and treatments such as grazing intensity often cannot be isolated in large, long-term data sets (Bock et al., 1993). The lack of studies is significant, since causes of vegetation change in semiarid regions are controversial in the absence of clear data (Havstad, 1996).

In this context, our goal was to document long-term vegetation change in a semiarid grassland and examine grazing impacts by organizing our research around spatially explicit historical information. We focused on a sandy plains ecosystem consisting of grasslands dominated by black grama (*Bouteloua eriopoda*) and dropseeds (*Sporobolus* spp.),

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and shrublands dominated by sandsage (*Artemisia filifolia*), with a long-term record of vegetation and land use. Other studies of grazing effects are typically small-scale and of short duration. Conversely, long-term and large-scale historical analyses usually lack good information on the spatial and temporal distribution of grazing. Here we take advantage of a historical data set that encompasses a study area greater than 40,000 ha, spans 140 years, includes a pre/early grazing baseline and a subsequent prolonged grazing history, and a large grazing exclosure established in 1943. Although historical information is often used to assess vegetation change (Bahre, 1991), and some studies have described landscape (e.g. soils), climate, and management effects on vegetation compared to early and mid-20th century baselines (e.g. Asner et al., 2003; Hennesey et al., 1983; Ludwig et al., 2000), our application of 1800s' archival data to examine a mechanism across subsequent treatments is rare. This 1800s' baseline presumes historical conditions of low or short duration impacts compared to intensive land use across the region in the late 19th and early 20th centuries (a pattern generally reported for the southwestern United States, e.g. Bahre, 1991, but locally specific information about early land use is often lacking, as in this study). Using this approach, we were able to quantify long-term vegetation change and better understand how early and more recent grazing patterns may have impacted the historical grassland of the study area.

In the course of our analysis we encountered limitations common to long-term observational studies, including information gaps, poor resolution of multiple and interacting variables (e.g. grazing, climate, and soil erosion), and constraints on the study design. We made note of these issues and in particular recommended a vegetation record intermediate between baseline and current periods. We also suggested how spatial results from this study might support restorative management and discussed management options when links between grazing and vegetation change are tentative.

2. Study area and methods

2.1. Study area and grazing history

The 44,417-ha study area was located at 1400–1500 m elevation in the northern Jornada Basin of New Mexico, USA, near the northern limit of the Chihuahuan Desert (Appendix 1, electronic version only). This location complemented other studies in the region where long-term vegetation change has been documented. While much of this historical research on semiarid grasslands has focused on the southern Jornada Basin (summarized in Havstad et al., 2006), a few studies (Ludwig et al., 2000; Muldavin et al., 2002; York and Dick-Peddie, 1969) investigated vegetation change elsewhere in southern New Mexico, and York and Dick-Peddie (1969) documented sandsage invasion north of our study area.

We obtained climate summaries for 1939–2000 for Bingham, New Mexico, 40 km north of the study area (USDC National Oceanic and Atmospheric Administration Western Regional Climate Center, 2007). Average annual precipitation is 27 cm and is far exceeded by average annual evaporation of 266 cm per year. About half of this precipitation (13 cm) occurs as localized monsoons in the summer months. July is the hottest month with an average temperature of 15.9 °C and January is coolest at 2.3 °C. Both droughts and wet periods occurred regionally and often over the time period studied (Sheppard et al., 2002). Severe droughts occurred across the southwestern US in the mid and late 1800s, 1930s and 1950s. Above average precipitation characterized the 1860s, the early decades of the 1900s, and 1941. Since the 1970s summer precipitation has been inconsistent, wet winters have increased and average annual temperatures have risen.

The study area boundary largely traced a mid-scale watershed comprised mostly of rolling sandy plains (85%) with scattered clayey and gypsic flats (Johnson et al., 1988; Neher and Bailey, 1976). A lava flow that impinges the southwest margin of the study area was excluded due to its different geology and vegetation. Modern landcover consists of semiarid shrublands (59%) and grasslands (30%), with the remainder classified as mixed types (spatially indistinct grasslands and shrublands) and infrastructure (Muldavin et al., 2000; USDI Bureau of Land Management, 1979). The sandy soils support sandsage shrublands and black grama and dropseed grasslands, along with scattered shrubs such as soaptree yucca (*Yucca elata*) and Mormon tea (*Ephedra trifurca*). Alkali sacaton (*Sporobolus airoides*), fourwing saltbush (*Atriplex canescens*) and gypsophyllic plant communities occur in the flats. Based on physiography, Donart et al. (1978) mapped the potential vegetation of the sandy soils as black grama and dropseed grasslands with soaptree yucca and some areas of sandsage.

According to historical accounts the Jornada Basin was intermittently grazed until the late 1800s and early 1900s, when stocking rates swelled regionally (Fredrickson et al., 1998; Williams, 1986; Wooten, 1908), although detailed records for the study area were not available. Sheep grazing prevailed in New Mexico from the 16th through much of the 19th centuries and was largely replaced by cattle grazing by the 1880s. Grazing levels remained high until the 1930s when federal agencies regulated livestock numbers on public lands. In 1943, the eastern two-thirds of the study area were condemned by the US Department of Defense to create White Sands Missile Range and livestock were removed. There was occasional trespass by cattle, a resident wild horse herd until 1999, and African oryx (*O. gazella*) were introduced to the missile range in 1969 (personal communication, Bureau of Land Management and White Sands Missile Range staff). While the historical density of horses on the range is not known they were likely constrained by a lack of watering sites. Grazing continues to the present in the western third of the study area, which mainly includes public lands managed by the Bureau of Land Management (BLM) and small amounts of state and private land. Since the 1940s the stocking rate in the grazed site fell substantially; e.g. the largest grazing allotment of the study area decreased from 22 ha per animal unit to 58 ha per animal unit in 1999 (BLM allotment records).

2.2. Reconstructing historical vegetation

We reconstructed historical vegetation from US General Land Office surveys (GLO) of the 1800s and compared historical and modern vegetation in a Geographic Information System (GIS). GLO surveys, despite shortcomings (e.g. uncertain plant names and abundances, protracted survey periods) provide the most spatially explicit historical vegetation data available for large tracts of land in the US (Bahre, 1991). They are typically archived at BLM state offices and are increasingly accessible from the internet (USDI Bureau of Land Management, 2007a). Forty-two percent of the study area, mostly in the future exclosure, was surveyed between 1880 and 1889, and 50%, spanning both the future grazed site and exclosure, was surveyed between 1855 and 1859 (Fig. 1). A 1920s survey of the southeastern part of the study area was omitted to limit the baseline to the 1800s, as were so-called township boundaries irregularly surveyed over time and the border between the future grazed site and exclosure. GLO surveys were conducted along 1.6 km (1 mile) section lines that form the Public Land Survey System grid (PLSS; USDI Bureau of Land Management, 2007b). Surveyors recorded plant species or lifeforms (grass, shrubs, trees) and qualitatively described their abundances. This information was provided in GLO surveys as vegetation summaries for each north–south and east–west running section line. Examples of vegetation summaries were "grass",

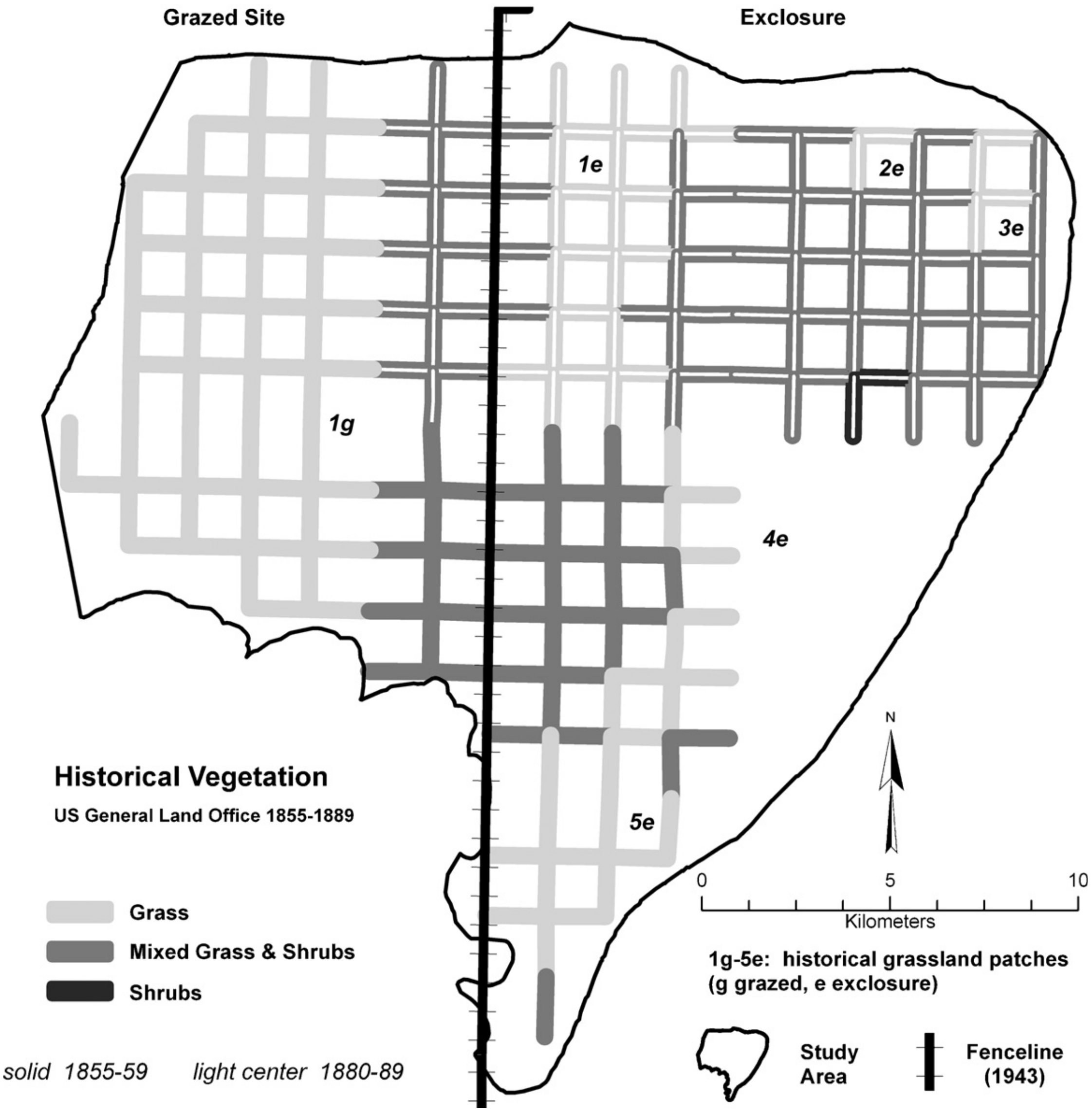

Fig. 1. Historical survey dates and vegetation reconstruction. Surveys were conducted by the US General Land Office (GLO) in 1855–1859 and 1880–1889 for 1.6 km (1 mile) section lines comprising the US Public Land Survey System (PLSS). Historical vegetation was reconstructed for 227 section lines. Historical grassland patches are labeled 1g (grazed) and 1e–5e (exclosure).

"good grama grass", and "grass, scattered brush." We classified such descriptions into three simple classes and ignored the ambiguous abundance references. Section lines with only grass recorded were assigned to grassland, those with only shrubs were assigned to shrubland, and those with both were assigned to mixed. An exception was made when soaptree yucca (*Y. elata*), a grassland indicator stem-succulent shrub, was recorded with grass. Those section lines were assigned to grassland rather than mixed. We used all three classes for the vegetation reconstruction. However, because our focus was the fate of the historical grassland, and the dominance of grass vs. shrubs was not clear in the mixed class, we excluded that class from our vegetation change analysis.

We adopted the publicly available 1999 PLSS GIS layer from BLM in New Mexico as our spatial representation of section lines. We buffered section lines 100 m per side to approximate the visual scope of the GLO surveyors, and attributed them with the historical vegetation classes. This map served as our reconstruction of past vegetation of the study area. To construct a parallel spatial grid for modern vegetation we merged two existing vegetation maps, one for the grazed site and one for the exclosure. The grazed site map was based on BLM staff interpretations of field data and aerial photos during 1975–1977 (USDI Bureau of Land Management, 1979). Plant community dominants and indicators, as well as landforms and soils were the attributes used to classify map units. The exclosure map (Muldavin et al., 2000) also was based on field data and aerial photos but additionally incorporated LANDSAT satellite imagery dated 1991–1995. Map unit attributes were similar to the grazed site map except that a quantitative guideline, $\geqslant$25% shrub cover, typically distinguished grasslands from shrublands. For comparison to historical vegetation we reduced the modern map units into grass and shrub-dominated classes and omitted ambiguous types. We assigned the grazed site map's Yucca and Grass map units to grassland and Creosote, Mesquite, Sagebrush and Saltbush to shrubland. We assigned the exclosure map's Black Grama Lava Grassland, Desert Plains Grasslands and Piedmont Desert Grasslands map units to grassland and Mesquite Shrubland and Sandsage Shrubland to shrubland. We did not retain the exclosure map's Lowland Basin Grasslands and Vegetated Gypsum Outcrop map units since they combined grasslands and shrublands that were not spatially distinguished (e.g. alkali sacaton vs. saltbush plant communities and hairy coldenia, *Tiquilia hispidissima*, vs. gyp dropseed, *Sporobolus nealleyi*, communities).

Since the GLO surveys lacked quantitative data, it is uncertain how well the historical and modern cover-classes agreed. Likewise, the more quantitative basis of the modern exclosure map raised questions how well it conformed to the modern grazed site map. We determined, however, that the critical designation of grass vs. shrub dominance was adequate for our analysis. Although our merged modern map spanned as much as two decades (1970s–1990s), it seemed satisfactory for representing the modern comparative period. We reasoned that major changes in shrubland distribution probably did not occur over such a short time, and that this map contained the best vegetation information available. To corroborate our use of the merged map, we also compared the historical vegetation to the 2004 Southwest Regional GAP Analysis Project landcover map (SW ReGAP; Utah State University, 2004). SW ReGAP had the advantage of a consistent classification, mapping technique and time period. Our hypothesis was that if results using the SW ReGAP map were similar to those of the modern map that would support our use of the modern map. We did not use SW ReGAP in our formal analysis because, despite its advantages, it is not recommended for application at scales smaller than counties.

It should be pointed out that grass cover in the modern shrubland map unit varied and was not always known. This limited our ability to understand the implications of shrubland invasion we report in this paper. For example, we could document that shrublands invaded those areas where they were not recorded historically, but without more information about co-occurring grass cover, associated ecological dynamics such as degraded grassland processes could not be confirmed.

The merged modern map was clipped to the buffered section lines of the PLSS and overlaid onto the historical data. We assessed vegetation change over time (1800s to modern) and between the grazed site and exclosure. The modern shrubland was constructed to quantify the spatial extent and intensity of shrubland invasion on the historical grassland, and the modern grassland allowed us to identify current grassland patches occupying the historical grassland. We used three metrics for our analysis: (1) *Invasion extent* as measured by the percentage of the total number of historical grassland section lines with any amount of shrubland invasion (where shrubland covered any part of a section line). (2) *Invasion intensity* as the median percentage of shrubland invasion per section line, and the percentage of the total number of historical grassland section lines with specified levels of invasion. These intervals were 0%, 1–4%, 5–24%, 25–49%, 50–74%, 75–94% and 95–100% invaded. (3) *Changes in grassland patch size*, where patches were defined as single to adjoining grassland section lines (a one-section line patch was an isolated grassland section line, a five-section line patch contained five grassland section lines joined at their ends, etc.). We use the term shrubland invasion because our analysis detected shrublands on the historical grassland, and not individual shrubs.

By excluding areas where both grass and shrubs were recorded historically from the vegetation change analysis, ignoring GLO abundance references, and attributing section lines but not the PLSS matrix (1.6 km^2 areas bound by section lines), our method differed from other GLO reconstructions of semiarid vegetation in New Mexico. Buffington and Herbel (1965) designated a historical class with no shrubs (similar to ours) but interpreted woody plant abundances to reconstruct shrub cover-classes (e.g. 15–55% creosotebush cover [*Larrea tridentata*]), regardless of co-occurring grass cover. Muldavin et al. (2002) interpreted abundances of all species to assign historical vegetation data to grass or shrub-dominated vegetation classes. Gibbens et al. (2005) reconstructed grass and shrub classes separately, even if recorded on the same section line, interpreting abundances for grass (e.g. poor or good grass) but not shrubs (e.g. the creosote class denoted that shrub's presence in any amount). York and Dick-Peddie's (1969) method appeared to be a hybrid; some vegetation classes seemed to express relative grass or shrub dominance and others simply presence, but we were uncertain as they did not provide details. All of these studies assessed vegetation change completely across their study areas and interpolated section line vegetation to the PLSS matrix. Their past/present comparisons ranged from shrub or shrubland invasion of areas where no shrubs were historically recorded, to changes in relative dominance of grass and shrubs. Compared to these studies our approach was conservative for assessing vegetation change. Its disadvantage was that by restricting analysis to a strictly delimited historical grassland, it did not estimate change comprehensively across the study area nor assess changes in relative species dominance.

2.3. Study design

Our study was designed to test the hypothesis that grazing was associated with shrubland invasion across the study area following the 1800s baseline period and with current differences between the grazed site and exclosure. As with many long-term observational studies, treatments and other elements were inherited and not experimentally assigned for optimal statistical analysis (Brown and Waller, 1986). In our case the dividing north to south fence provided two large treatment areas with no replicates, an inherited limitation given the study area configuration. The historical reconstruction grid delimited 227 section lines representing 32 ha each (200×1600 m), 90 in the grazed site and 137 in the exclosure, which we considered our sample units. Of these, 62 in the grazed site and 54 in the exclosure (116 total) comprised the historical grassland and were used to assess vegetation change. We considered analyzing the sample units of the two treatments directly using independent-sample tests, but were dissuaded from doing so because the absence of randomly located spatially interspersed treatment replicates violated assumptions of such tests. Additionally, other study limitations (discussed below) persuaded us that, although statistical results may be informative even without treatment replicates (Oksanen, 2001), their application was questionable and the overall study design, with its long time step and large geographic coverage, could elucidate major patterns without a statistical inference.

3. Results

3.1. Shrubland invasion extent and intensity

The historical vegetation was predominantly grassland (51% of section lines) or the mixed grass/shrub type (48%; Fig. 1). Grassland extent was comparable for the modern grazed site and exclosure, with 62 and 54 section lines, respectively. The mixed class was more prevalent in the exclosure than the grazed site (81 vs. 28 section lines). The historical shrubland occurred only in the exclosure and comprised just two section lines. All 62 of the grassland section lines in the grazed site formed a single patch while the exclosure had 5 smaller grassland patches that varied in size from 2 to 20 section lines (mean $= 10.8$).

Shrubland invasion became widespread in the historical grassland over the 140-year time span (Fig. 2). With respect to invasion extent (percentage of the total number of historical grassland section lines with any amount of shrubland), 87% of historical grassland section lines were invaded. Invasion intensity (median percent-invaded per section line and the percentage of the total number of historical grassland section lines with specified levels of shrubland) was generally high. Median invasion per section line was 83%. High levels of invasion, where at least 50% of a line became occupied by shrubland, occurred on 66% of section lines (Appendix 2, electronic version only; percentages are separate for grazed site vs. exclosure historical grassland section lines). Less intense invasion ($<$50% per section line) occurred on 21% of section lines, and only 13% of the original grassland section lines had no shrubland invasion.

While invasion extent was widespread in both the grazed site and the exclosure it was higher in the grazed site, where 94% of its section lines were invaded, compared to 80% in the exclosure (Fig. 2; Appendix 2, electronic version only). Invasion intensity was also higher in the grazed site. Median invasion intensity of grazed site section lines was 94% vs. 68% in the exclosure. Thus half of section lines in the grazed site were very highly invaded ($\geqslant$95% shrubland), compared to 28% in the exclosure.

3.2. Changes in grassland patches

Grassland patches decreased in size across the study area but this was more evident in the grazed site, where the single large historical grassland patch was broken into three small patches (Fig. 3). Mean patch size in the grazed site (average of number of adjoining section lines per patch) fell from 62 to 1.3 section lines. In the exclosure, three of the original five moderate sized grassland patches were eliminated leaving two patches, and mean patch size dropped from 10.8 to 3 section lines. The largest modern patch in the exclosure was 2.5 times that of the grazed site (five section lines vs. two). Invasion extent and intensity for the grazed site patch were the same as that of the site as a whole because there was just one historical patch (94% of section lines were invaded with over half of lines at least $\geqslant$95% invaded). This was higher, on average, than the exclosure, although results varied by exclosure patch (Fig. 2; Appendix 3, electronic version only). Invasion extent ranged from 50% to 100% for the five exclosure patches and median patch size, denoting invasion intensity,

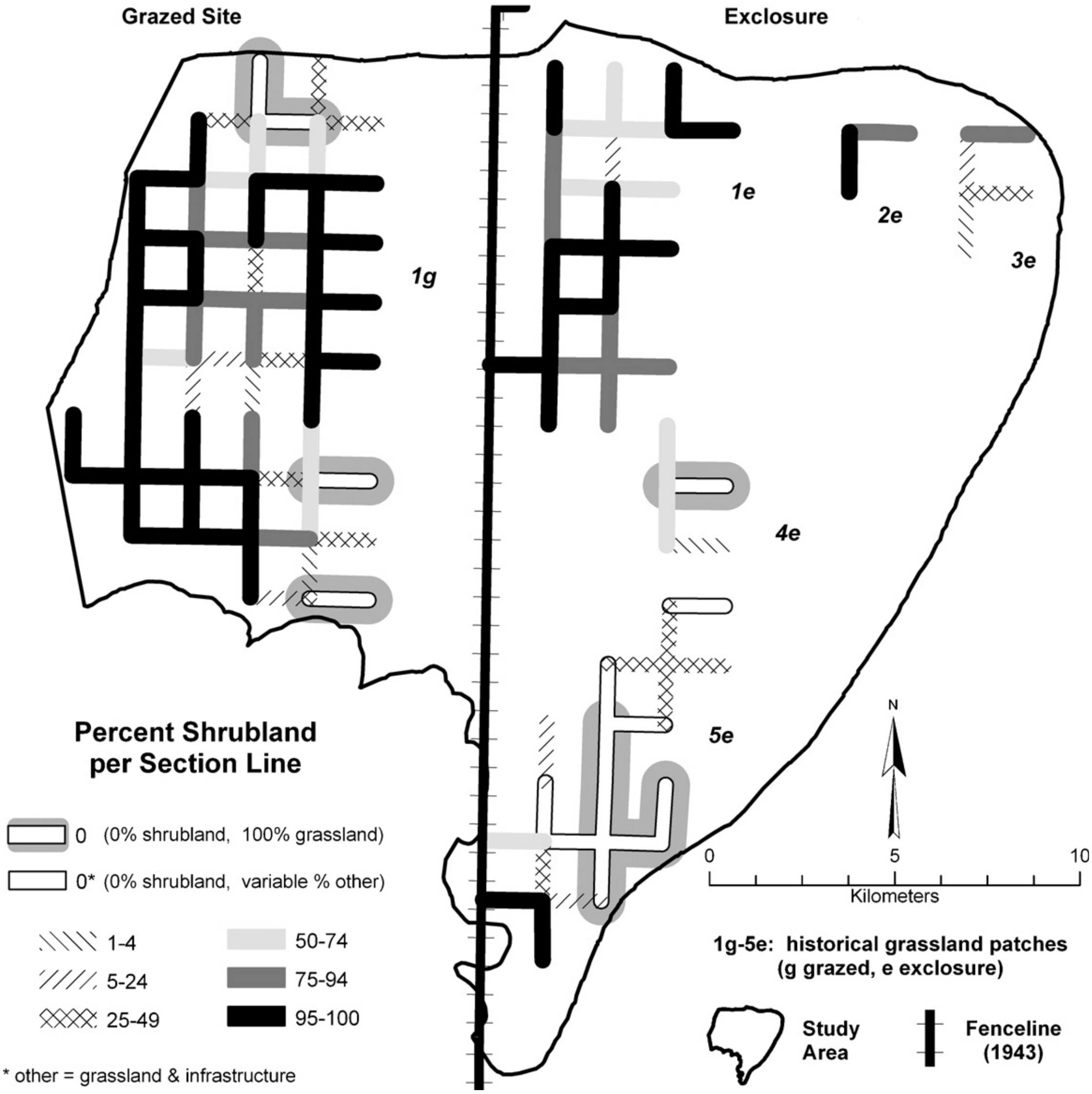

Fig. 2. Map of shrubland invasion. The vegetation change analysis was restricted to these 116 section lines of the reconstructed historical grassland. Invasion extent refers to historical grassland section lines with any amount of shrubland. Invasion intensity is depicted by the different percentages of shrubland per section line. For example, 87% of historical grassland section lines were invaded (invasion extent; hashed and solid lines), and 66% of section lines became at least half shrubland (invasion intensity; solid lines). Invasion was higher in the grazed site. Section lines with no shrubland invasion were 100% grassland or those with grassland and up to 12% infrastructure (e.g. roads). Historical grassland patches are labeled 1g (grazed) and 1e–5e (exclosure).

varied from 7% to 95% (for example, half of exclosure patch-1's section lines but only 10% of those of exclosure patch-5 became over 50% shrubland).

3.3. Acceptability of the modern map

Results of the overlay of the SW ReGAP landcover map onto the historical grassland were similar to our original analysis in that high shrubland invasion across the study area was evident and invasion was somewhat higher in the grazed site than the exclosure (Fig. 4). Compared to the original analysis, invasion extent rose an average of 14% in the study area. Invasion intensity, as measured by the median percent-invaded per section line, fell an average of 29%. The gap between the grazed site and exclosure medians widened from 26% in our modern vegetation map to 32% using SW ReGAP. While these differences are noticeable, we think the basic trends of shrubland invasion were similar when comparing either SW ReGAP or the modern map to the historical grassland and generally corroborate our use of the modern map.

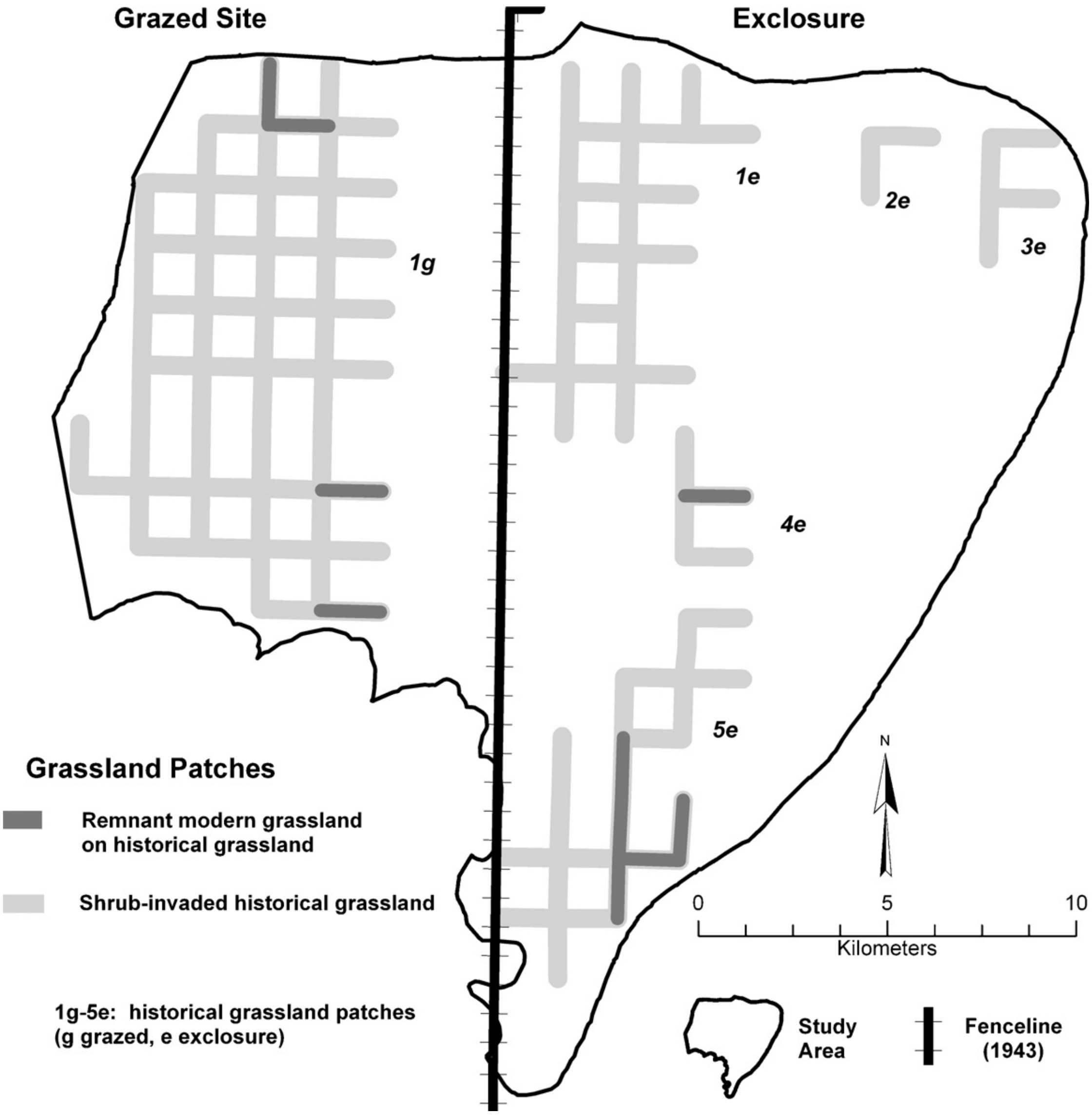

Fig. 3. Map of changes in historical grassland patches. Patches are defined as single isolated to multiple adjoining grassland section lines. Five relict modern grassland patches overlie the substantially larger historical grassland patches (labeled). Patch size decreased across the study area and more so in the grazed site.

3.4. Modern vegetation outside the delimited historical grassland

Although the focus of our study was vegetation change in the historical grassland (where only grass was recorded), our GIS comparisons revealed “new” grassland section lines outside of this area. Twelve modern grassland section lines (100% covered by modern grassland map units) were mapped outside the historical grassland, seven in the grazed site and five in the exclosure. A total of 41 section lines outside the historical grassland (including those 12) were at least 50% covered by grassland. Of these, 16 occurred in the grazed site and 25 in the exclosure. Section lines outside the historical grassland were difficult to interpret because they overlaid the historical mixed class, with its uncertain dominance of grass and/or shrubs. Depending on how a historical mixed class section line is interpreted, a “new” grassland section line might occupy a historically grass dominated section line (and so not be new), shrub steppe or shrubland. Any analysis of vegetation change for the historical mixed class would be hampered by this information gap in baseline vegetation. However, we did map these modern grassland section lines and those at least 50% grassland outside of the historical grassland (Fig. 5). This included section lines in the southeast portion of the study area surveyed by the GLO in 1920–1929. Although we did not interpret these section lines with regard to vegetation change they provided information about restoration potential, which we discuss below.

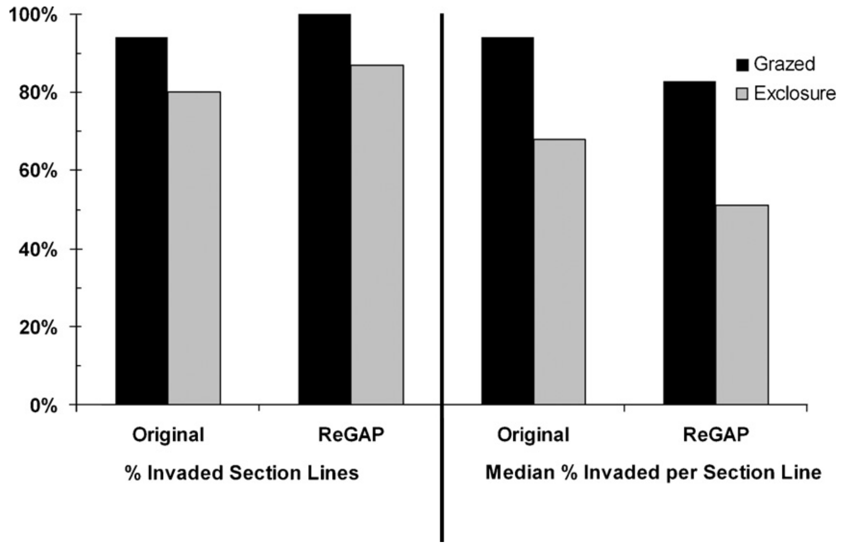

Fig. 4. Comparative analysis using Southwest Regional Gap Analysis landcover (SW ReGAP). Historical vegetation was compared to SW ReGAP to corroborate our use of the merged modern map (labeled "original" in chart). Overall results were similar, with high shrubland invasion extent (percent of invaded section lines) and intensity (median percent-invaded per section line) across the study area, and higher invasion extent and intensity for the grazed site.

4. Discussion

4.1. Vegetation change and grazing

Our analysis showed that grasslands covered a large part of the northern Jornada Basin of New Mexico in the mid to late 1800s and since have become substantially invaded by shrublands. These results agree with other long-term studies in the northern Chihuahuan Desert that documented steep declines of historical grasslands and increases in woody vegetation (Buffington and Herbel, 1965; Gibbens et al., 2005; York and Dick-Peddie, 1969). The current presence of shrublands across most of the historical grassland of the study area, against a backdrop of heightened regional livestock numbers in the late 1800s and early 1900s, suggests that early grazing fostered shrubland invasion. This is qualified by information gaps about early land use and vegetation after the 1800s' baseline but before the 1943 exclosure as discussed below. The fact that our three indicators of vegetation change—invasion extent, intensity and changes in grassland patches—were higher in the grazed site suggests grazing effects in the exclosure, although this is tempered by the high level of invasion regardless of treatment. It is also tempered by the pattern of decline of the historical grassland patches, which exhibited a fair amount of variability in the exclosure.

One proposal to explain ubiquitous shrublands in both the grazed site and exclosure is that early grazing impacts, perhaps combined with other factors (e.g. drought, soil erosion, reduced fire) led to extensive shrubland invasion across the study area prior to the 1943 exclosure, or triggered woody invasion trajectories by initiating desertification processes that take decades to unfold (Peters et al., 2006). In either case, subsequent differences in vegetation between treatments might have been muted (as we observed), since shrublands would have established before 1943, or the stage for initial or accelerated invasion would have been set. In their long-term study in the southern Jornada Basin Buffington and Herbel (1965) documented large shrubland increases by the 1910s, confirming that substantial early invasion was possible. In fact, a 1937 vegetation inventory (New Mexico BLM archives) mapped sandsage in the historical grassland of both the future grazed site and exclosure of our study area, but the map was limited in geographic extent. Decreasing livestock numbers in the grazed site from the 1940s on (BLM allotment records) and regional climate events favoring shrubs (1950s drought: Herbel et al., 1972; increased late 20th century winter precipitation: Brown et al., 1997), could have further obscured treatment differences. Interestingly, the steepest increase in shrublands in Buffington and Herbel's study occurred 1928–1963 after the heaviest grazing had subsided. This apparently nonlinear spatiotemporal rate (Fig. 6) suggests gradual increases in shrublands driven by local scale processes through the grazing period, followed by rapid coalescence of shrublands at landscape-scale, consistent with Peters et al. (2006). Information about the growth of specific shrubland patches in relation to land use and climate would help confirm the importance of historical legacies, mechanisms and cross-scale ecological dynamics. While such a pattern was plausible in our study, the lack of intermediate vegetation data precluded its examination.

Not all explanations of vegetation change in semiarid ecosystems are predicated on grazing, and many emphasize interaction effects. Hennesey et al. (1983) and Brown et al. (1997), for example, measured shrub increases in the absence of grazing (although pre-exclosure grazing had occurred). Muldavin et al. (2008) confirmed climate (seasonal and annual

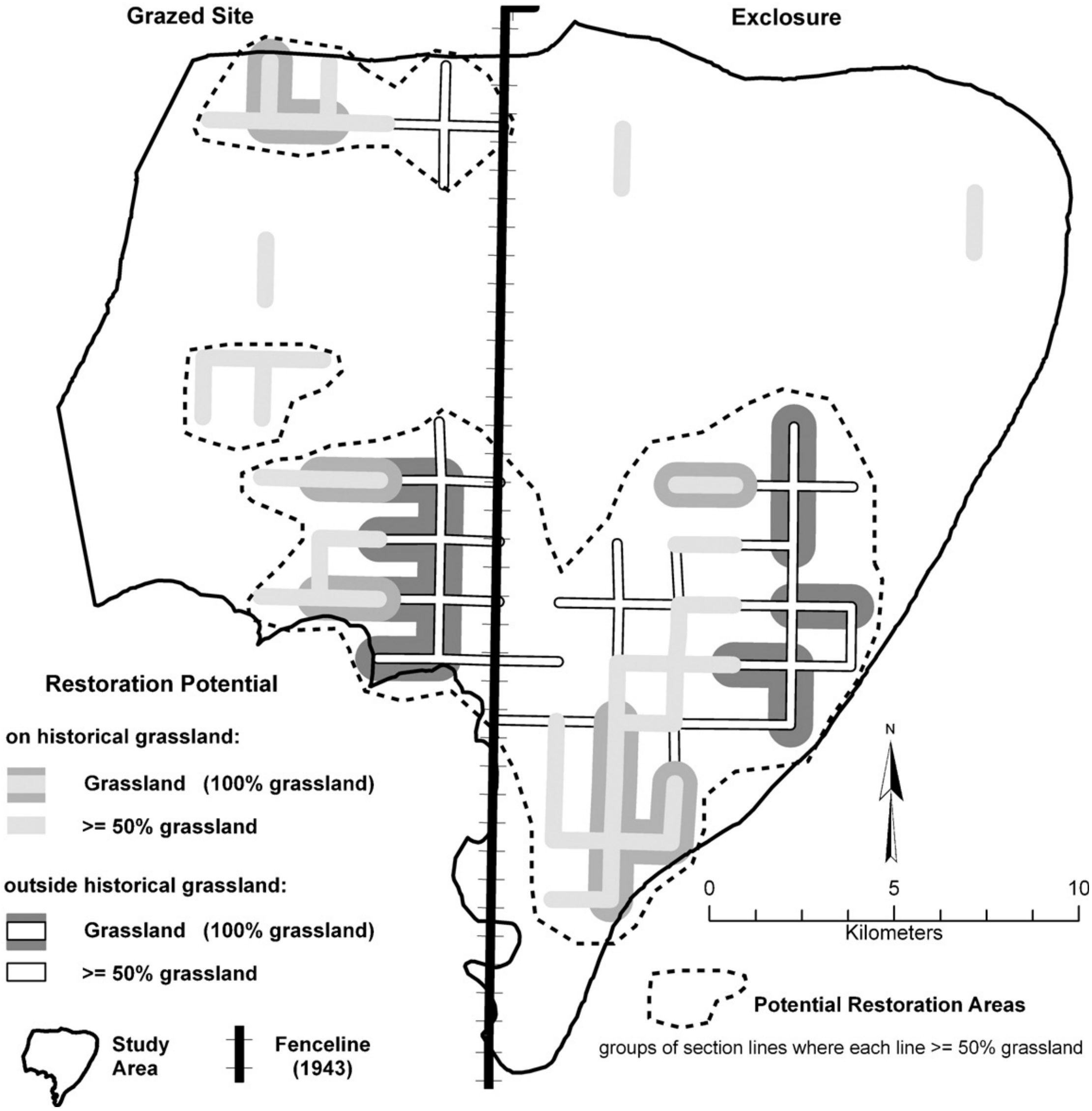

Fig. 5. Modern grasslands outside the historical grassland and restoration potential. Modern grassland section lines overlying and outside the historical grassland have light and dark "halos", respectively. It is unclear if grasslands outside the historical grassland are "new" or persistent since they overlie the historical mixed class for which dominance of grass vs. shrubs was not determined. Potential priority restoration areas are roughly outlined by dashed borders and form groups of adjoining section lines where each line is at least 50% grassland.

precipitation) as a chief driver of primary production of grasses and shrubs. Yao et al. (2006) identified diverse factors that interacted with drought at different scales to influence grass cover. The importance of soils was demonstrated by Herbel et al. (1972), who documented higher drought-induced black grama loss on deep sandy soils, Bestelmeyer et al. (2006), who determined that transitions to bare ground were more likely on non-calcic soils, and Asner et al. (2003), who reported woody plant cover highest on shallow clay soils. While reduced natural fire is cited as a factor in woody invasion in the southwestern US (Bahre, 1991; McPherson, 1995), the response of northern Chihuahuan Desert grasslands is not well known but appears sensitive to precipitation. For example, Drewa and Havstad (2001) recorded black grama decline even 4 years after fire combined with drought, and Muldavin (unpublished) found that fire with drought produced nearly 80% die-off of black grama. Drewa speculated that black grama may be dependent on post-fire precipitation for recovery. In the following section we provide examples of challenges for confirming the effects of grazing, other variables and interactions such as these.

4.2. The historical approach: values and limitations

There are significant benefits to a century-scale perspective on vegetation change that cannot be derived otherwise but there are also limitations. For example, vegetation change may not be revealed over the short term if effects are delayed

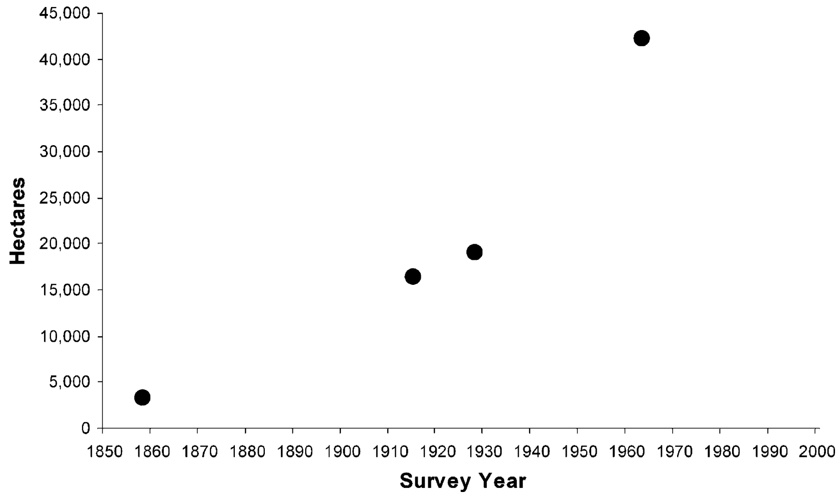

Fig. 6. Increase in shrublands in the southern Jornada Basin. Modified from Buffington and Herbel's (1965) Table 1, by totaling areas of 55–100% shrub cover-classes per survey year. We focused on these cover-classes instead of those with lower shrub abundances because they seemed more likely to suggest landscape-scale vegetation change, such as coalescence of shrub-dominated patches into high cover shrublands.

(Foster et al., 2003; Valone et al., 2002). Change may also be inconspicuous until spurred across thresholds and scales (Peters et al., 2006). In contrast, a drawback of long-term studies is that historical data often lack critical details (Swetnam et al., 1999) and historical conditions are adopted in situ and not structured for testing multiple variables and interactions (Bock et al., 1993).

In our study, five issues illustrated such limitations. The first regarded information gaps—we lacked data about early livestock use, fire history, soil processes, local climate and, notably, the abundance of shrublands shortly before 1943, when the study area was divided. Such information would confirm if vegetation change had occurred before exclosure establishment and if uneven livestock distribution was a factor. It would help to distinguish factors additional to grazing over time and between treatment areas. The second issue was that the two components of our modern vegetation map differed somewhat in classification and mapping technique. Also, both the 1800s and late 1900s comparative periods spanned multiple years, so vegetation change might have occurred within these periods. Our parallel comparison of historical data to the 2004 SW ReGAP landcover map indicated that these features of the modern map, while a concern, may not have been overly consequential. Baseline vegetation heterogeneity was the third issue. Vegetation of the 1800s was not regularly distributed across the study area in that the mixed (grass/shrub) class was more common in the exclosure. Conversely, the historical grassland patch of the grazed site was considerably larger than any of the five smaller grassland patches of the exclosure. This heterogeneity may have predisposed the study area for a particular course of shrubland invasion. The fourth issue was the exclusion of areas outside the historical grassland from the vegetation change analysis. While this avoided the uncertain (in grass vs. shrub dominance) mixed class, it limited our ability to examine vegetation change more thoroughly. The fifth issue concerned sampling constraints. Since we did not statistically analyze vegetation differences, our conclusions are interpretive and do not support inferences beyond the study area. Another sampling issue was that it is unknown how well our definition of grassland patches, adjoining grassland section lines, represented the actual configuration of vegetation in the landscape (e.g. Manies and Mladenoff (2000) found that modern vegetation section lines were not a good predictor of spatial features in the surrounding PLSS matrix; however, their GIS interpolation method differed from our approach).

4.3. Guidance for management in light of uncertainty about mechanisms

Regardless of the causes of vegetation change, the remaining intact and moderately invaded grasslands in the study area may be at risk of further invasion and shrubland dominance. This is supported by conceptual models (Archer, 1989; Peters et al., 2006) and evidence (Buffington and Herbel, 1965; Gibbens et al., 2005; Hennesey et al., 1983) that woody invasion of semiarid grasslands may be progressive and accelerated across temporal and spatial scales. If the rate of shrubland invasion in our study was linear and extrapolated into the future, all historical grassland section lines will have some degree of shrubland invasion by 2016 (based on a mean historical invasion rate of 0.72 section lines/year [101 section lines invaded in 140 years]). While admittedly crude (invasion rates may be nonlinear and future conditions may differ) such predictions can alert managers to the possibility of future grassland loss.

Given only moderate differences between the grazed site and exclosure and study limitations raised previously, what suggestions can be made for current management in the study area? Our main recommendation is for active monitoring and both preventative and adaptive management in a landscape context. This can help address possible future shrubland invasion, given the magnitude of historical invasion documented in the study area. We suggest that currently uninvaded grasslands and those with moderate levels of shrublands may be priorities for management. Section lines covered by at least 50% grassland seem a reasonable starting point. Including areas outside the historical grassland, these form three patches (dashed borders in Fig. 5). The southern-most patch is conspicuous due to its size and that it spans both Bureau of Land Management (grazed site) and White Sands Missile Range (exclosure), and so may be a landscape-scale opportunity for restoration and management across jurisdictions. The current vegetation of these patches, their accuracy for predicting the vegetation matrix (since our results are for section lines), and their landscape context (e.g. can patches be further expanded and connected?) could be verified using a combination of remote sensing and ground reconnaissance. Since our 50% "grassland threshold" is arbitrary, and criteria for prioritizing restoration are not well developed, it would be important to survey other areas as well for restoration opportunities.

5. Conclusion

Our study contributes to a regional literature documenting grassland decline in the northern Chihuahuan Desert and illustrates a strategy for studying mechanisms of vegetation change in long-term studies. Although our approach was simple, overlaying concurrent grazing treatments onto a historical baseline, we identified information gaps and other limitations that complicate conclusions. Perhaps foremost among these was the absence of an intermediate vegetation record. While results of increased shrublands over time and in the grazed site suggest that grazing influenced vegetation change, we acknowledge the mixed nature of the evidence. It is clear, however, that the historical grassland of the northern Jornada Basin in New Mexico decreased substantially over the past one and a half centuries. The preponderance of grassland section lines that became over 50% invaded indicates that areas still containing grasslands may be at risk of invasion or conversion to shrubland. Accordingly, we recommend monitoring and preventative and adaptive management of grazing and other land uses in the study area. The maps of historical and current grasslands produced in this study provide a reasonable starting point for restoration efforts.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.jaridenv.2008.03.012.

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