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Using historic data to assess effectiveness of shrub removal in southern New Mexico

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Abstract

In the late 1930s, the presence of a highly organized labor force, the Civilian Conservation Corps (CCC), in the Jornada Basin of southern New Mexico provided the capability for rangeland scientists to conduct experiments to determine the effectiveness of various techniques for remediating or reversing the encroachment of shrubs into grasslands. Unfortunately, soon after the treatments were performed, the CCC disbanded and most records of the treatments were lost. Despite sketchy documentation, some rangeland treatments left legacies on the landscape, and effects on water retention, erosion, and vegetation dynamics remained long after the CCC work ended. The discovery of historical documents from long-closed files and aerial photography in widely scattered archives allowed some of the experiments to be located and reexamined. Two research areas established in the mid-1930s were of particular interest, namely a tarbush (*Flourensia cernua* DC.) site where shrubs were grubbed and quadrats established and a creosote (*Larrea tridentata* [Sesse & Moc. ex DC.] Coville) site where the creosote and tarbush shrubs were grubbed. Here we outline how these sites were rediscovered, how historical measurements were repeated for the first time since the late l930s, and conclusions drawn regarding specific rangeland remediation strategies and vegetation dynamics. Our results show that shrub populations recovered from a radical removal treatment in less than 65 years. Remediation of these sites so that grass will recover to pre-shrub-dominated amounts will require measures additional to just removal of shrubs in

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order to restore hydrologic function. The fact that we were able to relocate, revisit, and resample these treatment areas provided unique opportunities to understand the long-term vegetation dynamics of these arid ecosystems. It is evident that woody plant populations have a high degree of resilience, that density dependence or interference appears to limit plant size in arid shrub communities, and that shrub populations had not reached any stable equilibrium state at the time of treatment in the 1930s. These insights would have been impossible to gain from short-term studies and without long-term studies initiated in the 1930s combined with recent discoveries of original documentation and historical aerial photography.

Keywords: Rangeland treatments and remediation; Chihuahuan Desert; Civilian Conservation Corps; Ecosystem stability; Shrub resilience; Long-term vegetation response; Historical datasets

1. Introduction

Arid ecosystems may experience the encroachment of brush or woody species into grasslands, usually accompanied by loss or reductions in grass cover, or the loss of plant cover altogether. In the southwestern US, as in other regions, there has long been interest in reversing degradation of such desertified rangelands. However, many constraints limit our ability to restore or remediate these systems: the expense of manipulating vegetation or resources over vast areas, lack of knowledge about the proximate factors limiting the recovery of forage grasses, and the slow response time of the system to perturbation.

From the mid-1930s to the early 1940s, numerous rangeland remediation treatments were performed in the western US owing to the availability of an inexpensive and highly organized labor force at CCC camps. Working with scientists and managers of various government agencies, these CCC enrollees were able to perform an enormous amount of conservation work in the West. With the advent of World War II, much of the work stopped and most detailed records of rangeland treatments were lost as the CCC disbanded in 1942. Despite sketchy documentation, some treatments to southwestern rangeland left legacies on the landscape. Effects on water retention, erosion, and vegetation dynamics remained long after the CCC ceased work. Useful information on the success of various treatments, rates of vegetation growth, and ecosystem stability could be obtained if the past activities could be documented and reconstructed.

Two major sources of data that would help in this reconstruction are any form of documentation in the files of government agencies involved and any independent data taken from the time of treatment installation to the present. These two types of data exist in the Jornada Basin of southern New Mexico where both the US Department of Agriculture, Agricultural Research Service, Jornada Experimental Range (JER) (783 km^2), and the New Mexico State University, Chihuahuan Desert Rangeland Research Center (CDRRC) (259 km^2), were host to several CCC camps. Searching old files has revealed some rough sketches of treatments, limited documentation of the exact treatment applied, and some baseline data taken before and during treatment application. Only a few instances of any post-treatment measurements were found. A second source of data, namely, medium-scale aerial photography, began in the 1930s and is more complete (Rango et al., 2002). Although significant gaps were evident in the 1950s and 1960s, a more complete picture of vegetation response to the treatments can be assembled using these photographs. The objectives of this paper are to (1) evaluate the current state of vegetation in two specific areas in response to shrub-removal treatments in the late 1930s, (2) determine changes occurring in the control quadrats over 60 years after initial treatments, and (3) summarize what can be learned about effectiveness of specific rangeland remediation strategies and about ecosystem stability.

2. Materials and methods

The Jornada Basin is generally classified as semidesert grassland, an ecosystem covering about 10.5 million ha in southwestern Arizona, southern New Mexico, western Texas, and northern Mexico. The region contains a complex mix of vegetation, ranging from some nearly pure stands of grass to nearly pure stands of shrubs. The increase of shrubs or brush in the Jornada Basin is well documented (Gibbens et al., in press). The extent of grass and brush on the JER was originally reported for the years 1858, 1915, 1928, and 1963 by Buffington and Herbel (1965). The data show a major shrub invasion taking place on the JER in a little over 100 years. It has been speculated that once the shrubs become established, the ecosystem becomes stable (Schlesinger et al., 1990; Reynolds et al., 1999), and this ecosystem has been described as multi-equilibrial (Bestelmeyer et al., 2003).

The overall goal of rangeland remediation treatments has been to effect a change in vegetation whereby grass will replace shrubs to some extent so that grazing potential will increase (Monger, 1999). Limiting grazing pressure was insufficient to reverse the shrub invasion of grasslands, and a consensus developed that shrub removal was necessary to initiate grassland recovery (Jornada Experimental Range, 1958). Later, it was suggested that removal of shrubs must also be combined with supplemental treatments like seeding with desired grasses (Abernathy and Herbel, 1973). Unfortunately, even these agronomic treatments were only marginally successful, at best (Ethridge et al., 1997).

The key component of these treatments was the removal of brush and a variety of methods was used. When an abundant and inexpensive labor force was available, mechanical and manual remediation approaches were possible over relatively large areas (Melzer, 2000). The CCC was able to hand grub (i.e. remove shrubs below the root crown) across large acreages of land in New Mexico and other states (Jornada Experimental Range, 1941). Seeding and transplanting grasses were also attempted, although with few successes. Barriers for water redistribution (in the form of soil dikes, terraces, furrows, and brush water spreaders) to increase local soil moisture were also meant to increase the chances for establishment of desirable vegetation (Rango et al., 2002). Exclosures to control livestock grazing or to exclude small mammals were constructed with variable levels of continuing maintenance

(Valentine, 1947; Havstad et al., 1999). Based on historical documents, we were able to relocate and reassess two examples of grubbing applied to Jornada brush sites.

Grubbing was used to clear tarbush (*Flourensia cernua* DC., at that time called blackbrush) from a 2.17-ha site on the south end of the JER. Approximately 80% of this area was grubbed free of tarbush in 1936 and 1937. The treatment and measurements made at this tarbush site were adequately documented in a periodic report and supported by ground photography (Jornada Experimental Range, 1937) but never published more widely. At about the same time on the CDRRC in a creosote (*Larrea tridentata* [Sesse & Moc. ex DC.] Coville)-dominated site south-east of the CDRRC headquarters, grubbing of creosote and tarbush was conducted over a much larger area, but documentation was incomplete. The grubbing was conducted in straight-line strips in 1936 and covered about 73 ha with about 67% of this area being grubbed free of creosote and tarbush (Agricultural Experiment Station, 1940).

2.1. Tarbush area

The tarbush study area was established along the east side of the main Jornada–Las Cruces road, approximately 1.33 mi (2.14 km) south of the South Well on JER. This study area is classified as a loamy ecological site within Major Land Resource Area 42, Southern Desert Unit SD-2 (USDA, NRCS, 1997). Some of the area had been grubbed free of tarbush (on December 22, 1936) before the vegetation assessment was made. The vegetation on the plots was surveyed by sampling with 1-m^2 quadrats arranged in a grid; these quadrats were then subdivided into square decimeters. The two control areas each measured 100 ft (30.48 m) $\times$ 250 ft (76.2 m); the original treated area (December 22, 1936) measured 125 ft (38.1 m) $\times$ 1320 ft (402.3 m), although only the first 250 ft (76.2 m) were used for measurements. The second treated area (March 3, 1937) measured 75 ft (22.86 m) $\times$ 250 ft (76.2 m). Ground photography of the treated and control plots was taken on April 22, 1937. Fig. 1 (top) was taken along the northern boundary between the control (left) and treated (right) areas, looking to the east. The entire treated area (both treatment areas) was regrubbed again in February 1939 by the CCC to remove any shrub regrowth. The exact spot (marked by a stake in 1937) for the photography presented in Fig. 1 (top) was located and the area rephotographed in the same way on June 25, 2002, Fig. 1 (bottom), to illustrate the recovery of tarbush in the grubbed area over 63 years (1939–2002).

The lack of formal site documentation had hidden the site and treatments from scientists on the Jornada ever since the 1960s. This area was also not covered in many aerial photographs until around 1970, presumably after significant regrowth in the grubbed areas, and was therefore difficult to locate in the photography. From cross-comparison of the sketchy historic records and perusal of popular, annual "Ranch Day" reports from the 1930s and 1940s, it was possible to locate the general treatment site. This allowed the relocation of the original quadrats. On July 24, 2001, 1-m^2 quadrat frames divided into decimeters were placed along the original tarbush transects, and live plant canopy cover (and basal area for grasses) in the quadrats

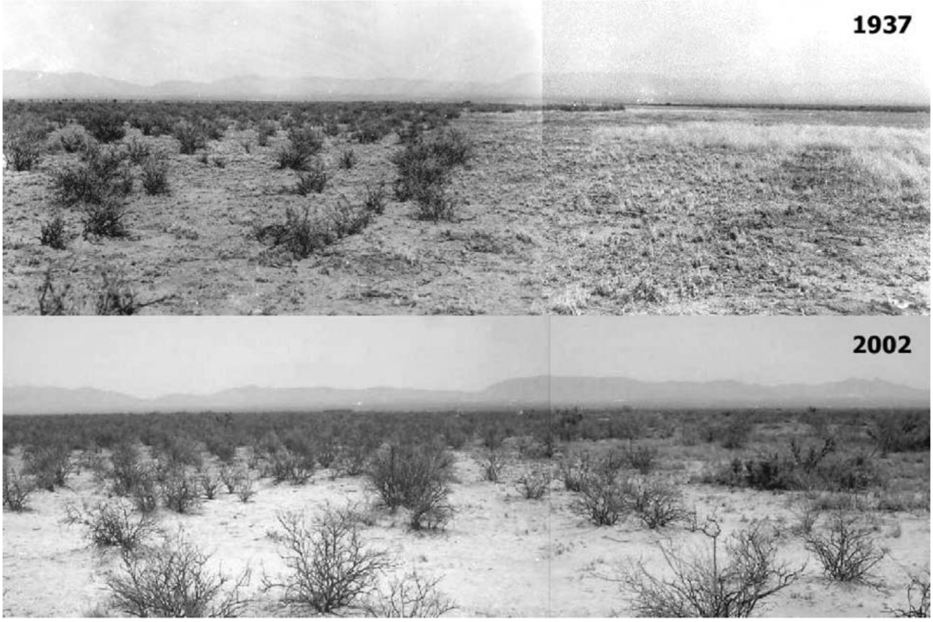

Fig. 1. Rephotography of the tarbush grubbing site. Top photo was taken on April 22, 1937, and bottom photo was taken at the same location on June 25, 2002.

was remeasured in the same way as done in March 1937. Change in cover (from 1937 to 2001) for plant species with sufficient sample size was analysed using analysis of variance (the GLM procedure; SAS Institute, Inc., 1999); tests of the residual plots showed that the data met ANOVA assumptions. In addition, we tested whether there was a difference in total cover in 2001 between control and removal quadrats. Due to nonnormality of the data, the quadrat cover totals were log transformed using $\log(x+1/6)$ (Kuehl, 2000) and unequal variances were fit using the MIXED procedure of SAS (SAS Institute, Inc., 1999).

All 40 quadrats in treatment and control areas were measured in July 2001. Due to limited sample size, it was necessary to make additional measurements in the treatment and control areas to determine whether any differences in shrub densities and individual shrub cover and volume exist today. Belt transects of 10×30 m were set up and we measured the size of each shrub inside the belts. The maximum width, perpendicular width and height of each tarbush and wolfberry (*Lycium berlandieri* Dunal) shrub in the belt transect were measured to the nearest centimeter. Wolfberry was selected for measurement because it represents the subdominant shrub species in this area. Three belt transects had to be located in the treated area in order to approach the number of shrubs encountered in the two belt transects in the control area. Belt transects were measured in July and November 2001. The volume (V) of each individual shrub was calculated using the equation for a cylinder:

$$V = ((0.5 \cdot d_{\rm m})(0.5 \cdot d_{\rm p}) \cdot 3.1415)(h), \tag{1}$$

where d_m is the maximum width of shrub, d_p the width perpendicular to d_m and h is the height of shrub.

The belt transects had to be placed in specific locations in order to avoid the quadrat grid area, cattle paths, and old roads; therefore, random sampling was not achieved. Because of this, it was deemed inappropriate to analyse these data using normal statistics; a difference between treatments will be simply defined as two different means with nonoverlapping standard errors.

To summarize shrub population recovery in the treatment area as compared to the control area, we generated shrub size class distributions of the belt transect individuals for both tarbush and wolfberry. Generated size class ranges were of equal size for controls and treatments of the same species. Frequency data were analysed using a χ^2 analysis of homogeneity. Due to low numbers in some of our size classes, Fisher's exact test was performed.

Vegetation spatial structure in the tarbush area was quantified using a "gap intercept" method (Herrick et al., in press). Gaps between plant canopies and between plant bases were recorded along each of the eight original 76-m-long linear transects in each of the two treatment areas (control and removal). The proportion of each line exposed in >50-cm-long gaps was calculated. For the canopy gaps, individual grass blades and shrub leaves intercepting the line were ignored: a canopy intercept was defined for this method as any 3-cm or longer segment with at least 50% canopy cover. A basal intercept was defined as any plant base that intercepted the edge of the tape.

2.2. Creosote area

In July to August 1936, a unique set of treatments was completed on the CDRRC in a predominantly creosote area. Creosote and tarbush shrubs were removed at the root level (grubbed) from a 72-ha area dominated by creosote. The area is classified as a gravelly ecological site within Major Land Resource Area 42, Southern Desert Unit SD-2 (USDA, NRCS, 1997). Mesquite (*Prosopis glandulosa* var. *torreyana* [L.D. Benson] M.C. Johnst.) and soaptree yucca (*Yucca elata* Engelm.) were left undisturbed. The geometry of this treatment was most striking in that it was not along the contour (as usually performed by the chief cooperator, the Soil Conservation Service, now the Natural Resources Conservation Service), but rather in straight linear strips, 30.5 m wide and 3.1 km long (Fig. 2). There were five grubbed strips separated by 15.25-m-wide ungrubbed or control strips. Brush was piled at the west edge of the ungrubbed strips, probably to serve as a barrier to slow water from running off the grubbed strips; however, as noted by Goslee et al. (2003), these brush strips are rapidly rendered ineffective by water and wind erosion. On October 10, 1939, creosote and tarbush regrowth was again removed from the center strip, but for only 253.6 m of the original 3.1 km, and all shrubs (creosote, tarbush, and mesquite) and yucca were removed from the strip to the east of the middle strip, again for only 253.6 m. These two retreatment areas totaled only 1.55 ha or about 2% of the original, total treated area. The only existing locational information was a schematic diagram of the treated strips found in the files of the CDRRC. Fig. 2

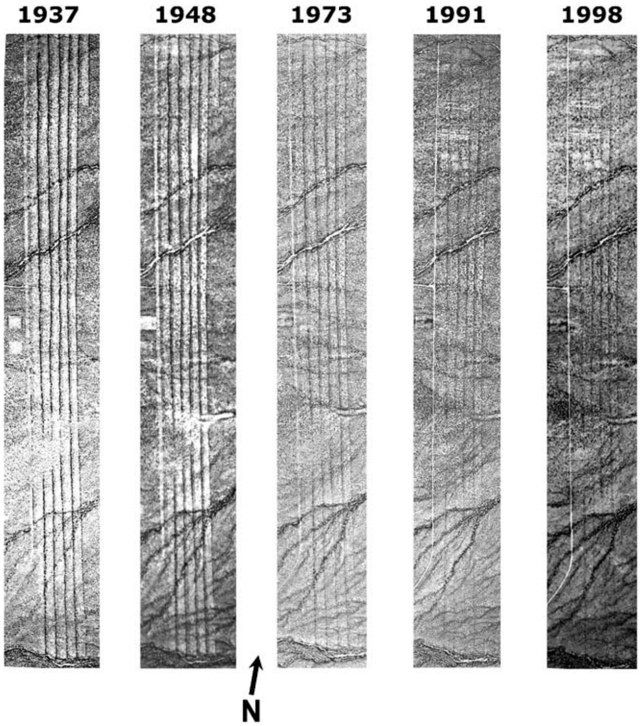

Fig. 2. Temporal sequence of alternating grubbed and ungrubbed strips in a predominantly creosote area in CDRRC, pasture 10, where original grubbing was performed in 1936. Aerial photos were taken from flights in 1937, 1948, 1973, 1991, and 1998 (Rango and Havstad, 2003).

shows a temporal sequence of the entire extent of these grubbed strips as they appear on aerial photography from 1936 to 1998 (Rango and Havstad, 2003). This long lasting, visible evidence led us to establish ground measurements in this area in 2001.

File records and published reports in the CDRRC, JER, and Soil Conservation Service field offices on this treatment were totally inadequate to document the extent of the treatment and its change with time. Fortunately, aerial photography, as shown in Fig. 2, has been available since 1936. Aerial photos were in fact used to determine where the October 10, 1939, re-treatment was performed and also to identify a sixth grubbed strip that was never reported in the northern portion of the treatment (see the upper right area of the strips in Fig. 2; Rango et al., 2002). It was stated in reports (Agricultural Experiment Station, 1940) that the re-grubbed strips would be kept free of brush whenever necessary. However, the 1939 regrubbing over the 1.55-ha area was apparently the last shrub removal treatment the strips received, probably because of the occurrence of World War II and the reduction of the labor force on the experimental ranges.

New measurements in the form of belt transects were initiated in 2001. In August and October 2001, nine 10×30-m belt transects were set up and measured. Similar to the belt transects in the tarbush treatment on JER, each creosote, mesquite, or tarbush shrub in the belt transects was characterized by measuring maximum width, perpendicular width, and height to the nearest centimeter. Four 10×30-m transects were located in the treated (grubbed) strips, three in the control strips, and two in the area outside the strips where treatments or measurements were never made and where no evidence of any other recent human activity exists. Because the creosote shrubs in this area have a more conical shape than tarbush shrubs, individual creosote volumes were calculated using the equation for a cone:

$$V = ((0.5 \cdot d_{\mathrm{m}})(0.5 \cdot d_{\mathrm{p}}) \cdot 3.1415)(0.3333h). \tag{2}$$

As a supplemental form of observation, aerial photos in the 1930s, 1940s, 1970s 1980s, and 1990s were used to monitor shrub regrowth and also to locate experimental exclosures in the strip area. This reference information facilitated the placement of our belt transects. Although easily visible on the aerial photos (Fig. 2), these radical treatments are surprisingly not readily visible on the ground. This presents a problem because scientists in subsequent years, not realizing that plots had been treated there over such an extensive area, have located their own new experiments in this area on top of the strips and near the road along the western edge of the treatments. As a result, our belt transects had to be located in the eastern part of the strips to be outside the influence of more recent manipulations. A difference between treatments was thus simply defined as means with nonoverlapping standard errors. As with the tarbush belt transect data, creosote bush size class distributions were generated and compared using a χ^2 test of homogeneity; Fisher's exact test was performed on the shrub frequencies.

3. Analysis and results

3.1. Tarbush site

Total plant cover area was higher in 2001 than in the original 1937 measurements in both control and removal transects. There were no significant differences in the increase of tarbush, wolfberry, or bush muhly (*Muhlenbergia porteri* Scribn. ex Beal) cover between the control and removal quadrats (Fig. 3). Although wolfberry cover seems to increase substantially in the removal plots, our small sample size limited our ability to detect a significant difference in the change in wolfberry between control and treatment quadrats. In the period from 1937 to 2001, the treatment plots, which were cleared of all tarbush, had recovered to a shrub and bush muhly grass cover approximately the same as the control plots had in 1937 (Fig. 3). At the same time, the tarbush on control plots continued to increase in cover, and bush muhly cover increased significantly in the control areas ($t = 2.32$, $p = 0.04$). In addition, due to the high variability among quadrats, total cover did not differ significantly between the control and removal quadrats in 2001 ($F = 1.95$, $p = 0.17$). Removal plots have recovered from the initial tarbush grubbing. Fig. 3 shows the mean cover for removal and control quadrats by species in 2001.

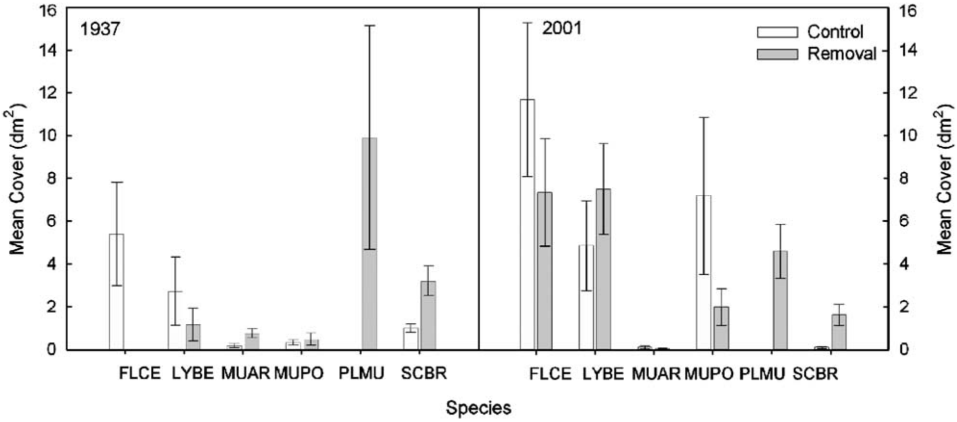

Fig. 3. Mean cover for control and removal quadrats by species for 2001, including tarbush (FLCE), wolfberry (LYBE), bush muhly (MUPO), ear muhly (MUAR), tobosa grass (PLMU), and burro grass (SCBR).

It is unclear whether the tarbush cover in either the control or removal areas had stabilized by 2001 or if the shrub population is continuing to expand. Over the almost 65 years between control quadrat measurements, the tarbush total cover in this specific quadrat area had an average annual growth rate of $1.45\,dm^2/100\,dm^2/y$. There is no way of knowing how this average growth rate varied in response to environmental conditions. The continued growth indicates that it was not stable when the treatment was performed in 1937.

Grubbing of the tarbush areas was originally completed in 1936 prior to obtaining any baseline measurements. In order to collect some pretreatment vegetation measurements, 40 quadrats were established in 1937, 20 in the control area, 5 in an area where removal took place after the measurements, and 15 in the area of the 1936 removals. Cover measurements were taken in 1937 in controls and removals. Therefore, only five intact removal area quadrats were measured prior to tarbush removal in 1937. The lack of pretreatment data for all 20 removal quadrats makes it impossible to examine differences in shrub cover between the two areas at the point of experiment initiation. Examination of grass cover, however, was possible with the 1937 data. The quadrat data shows that tobosa grass (*Pleuraphis mutica* Buckley), burro grass (*Scleropogon brevifolius* Phil.) and ear muhly (*Muhlenbergia arenacea* [Buckley] Hitchc.) grass cover were higher in the removal area than the control areas at the start of the experiment (Fig. 3). Grass response in the removal areas today is likely to be highly dependent on the differences originally present in these treatment areas, constraining the conclusions that we might draw. Nevertheless, this experiment offers important insight into the potential recovery of arid shrublands to severe disturbances.

Belt transect data at the tarbush site reveals several trends. As measured in 2001, the individual tarbush shrubs that have repopulated the treated plots have a mean volume and mean height greater than those in the control areas (Fig. 4a). Yet

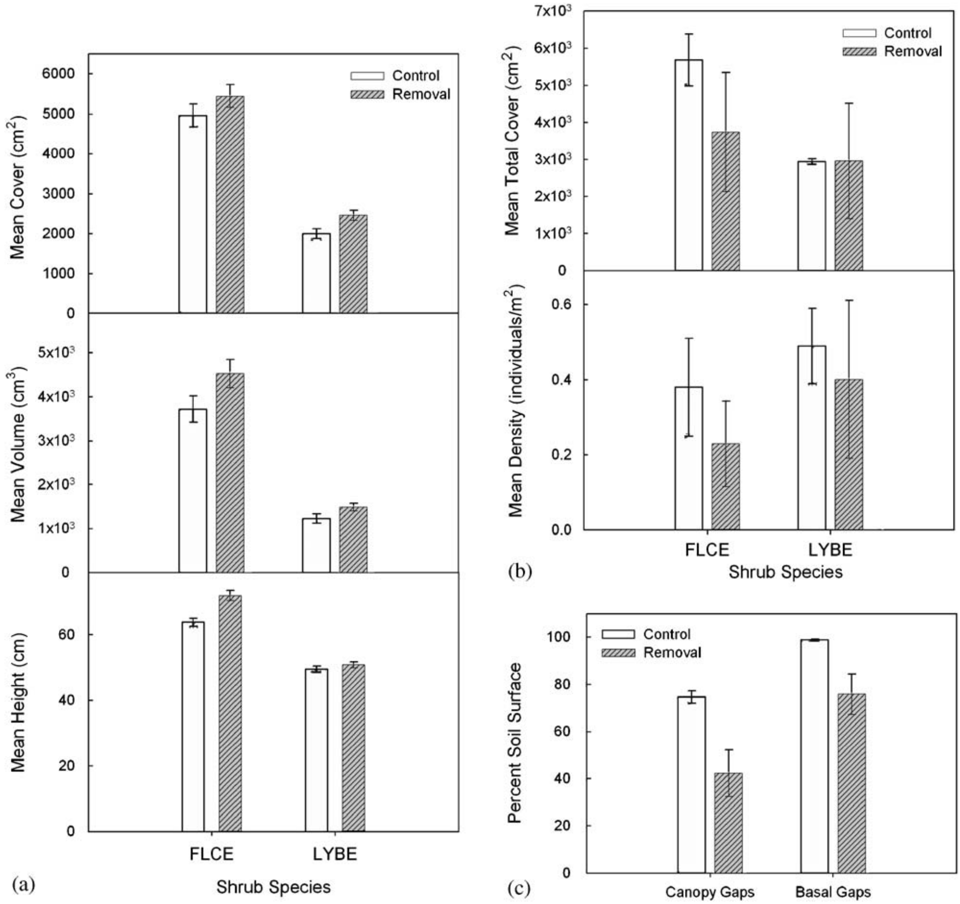

Fig. 4. Comparison of mean tarbush and wolfberry size (a), total cover and densities (b) between control and treated plots obtained using belt transects at the tarbush site. Comparison of plant canopy gaps and plant basal gaps (c) between control and treated plots using the gap intercept method. (Tarbush is FLCE and wolfberry is LYBE).

tarbush transect mean total cover and tarbush mean density were not significantly different (Fig. 4b), indicating that, although not statistically significant, the greater density in control plots is enough to offset the larger shrub size on the treated plots. Variability of tarbush density among removal sampling areas was high. Cover and volume of wolfberry individuals were also greater in the removal areas. However, height of individual shrubs, density and mean total transect cover showed no differences between control and removal areas (Figs. 4a and b), again reflecting that the greater densities of wolfberry on the control plots were enough to offset the significant increases in shrub sizes on the treatment plots. So while wolfberry and tarbush individuals in the belt transects in the removal areas were larger than those in the control, differences in density and mean total area cover were not different, supporting the results from the 2001 quadrat data that there was no difference in total cover between the control and removal sites.

Despite the lack of difference in total cover in the tarbush belt transects, vegetation structure was significantly different between control and removal plots (Fig. 4c). The proportion of the soil surface exposed in intercanopy gaps 50 cm or longer was significantly higher in the control than in the removal plots (t-test; $p = 0.019$). Soil surface exposed in gaps between plant bases was also higher (t-test for unequal variances; $p = 0.077$). This is likely due to an increased uniformity of plant spacing as new individuals became established in the removal areas.

3.2. Creosote site

Because quadrat measurements were not made at the creosote site in the 1930s, we have had to rely solely on the present day ground measurements (belt transects). Examination of the belt transect data at the creosote site points to some similarities to the tarbush site. The individual creosote shrubs that have repopulated the grubbed (treated) creosote strips had a greater mean cover, volume and height than individuals in the control strips (Fig. 5a). Creosote bush density, however, was double in the control area (0.28 shrubs/m$^2 \pm 0.03$) compared with the treated area (0.14 shrubs/m$^2 \pm 0.02$) (Fig. 5b). Because of this difference in shrub density, total mean cover was greater on the control transects than on the treated transects. Creosote bush size class distributions contradicted our expectations. Removal plots had a greater number of larger shrubs than the control areas, similar to what we found in the tarbush site ($\chi^2 = 32.8$, Fisher's exact test, $p < 0.0001$). It is also worth noting that the number of shrubs in the strip most recently cleared of all shrubs in 1939 (strip just east of middle strip) was considerably less than the strip cleared only in 1936 (the easternmost strip of the five parallel strips). There was no significant difference in the size distribution of individual shrubs between the middle strip and the easternmost strip. It is also apparent that the occurrences of mesquite and tarbush shrubs in the control transects were higher than in the treated transects. Because of the absence of shrub size data from the 1930s, we could not estimate mean growth rates in the undisturbed, control areas.

4. Discussion

These historical experiments provide us with an important (and rare) look at the long-term response of Chihuahuan Desert shrubs to removal. Long-lived woody plants, as individual organisms or as populations, are intrinsically difficult to study and may express responses to environmental stresses or perturbations over time periods that are impossible for a single investigator to follow. Hence, the historic remediation experiments reexamined here can give valuable insight into the response of creosote and tarbush (individuals and populations) to an extreme disturbance.

Apparently, shrub populations responded vigorously and robustly after the perturbation of the grubbing treatment. The tarbush removal took place at a site

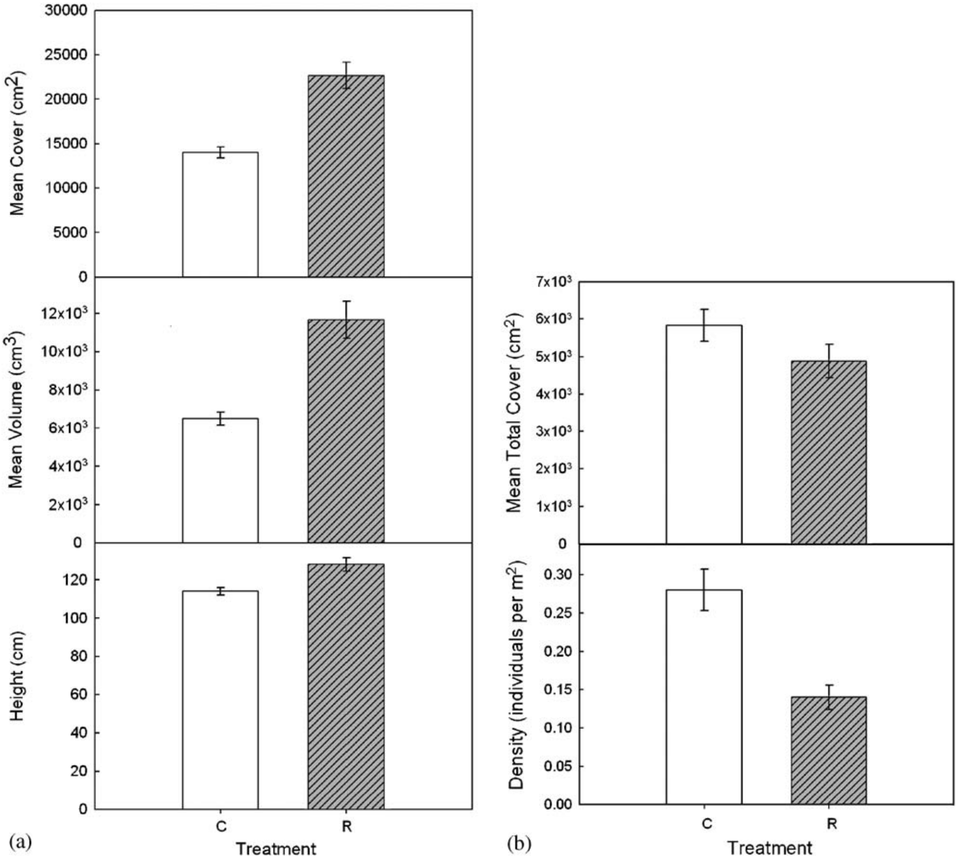

Fig. 5. Comparison of creosote size (a), total cover, and densities (b) for control (C) and treated (R) plots obtained within belt transects at the creosote site.

where the shrub population has continued to accumulate cover and volume (roughly doubling in shrub cover in the control plots over 60 plus years). The density of shrubs in the tarbush treatment area is only about half the density in the control areas, although patchiness and a relatively small sample area make it difficult to detect statistically significant differences. Low densities in much of the treated area, however, suggest that recruitment has been limited or at least has failed to occur rapidly enough to reach densities typical of undisturbed sites. Individual shrubs are larger, however, in the treated areas (quite possibly due to reduced competition or interference in the low-density neighborhoods). Of the five grubbed quadrats for which we have pre-treatment data, four contained tarbush individuals in 1937 before grubbing; not one of those quadrats contained tarbush individuals in 2001. It appears, then, that the shrubs in the treated areas today likely represent new recruits rather than survivors of the grubbing treatment. Wolfberry provides another example of patchiness; one of the treated transects has very high cover of wolfberry, but two others have very low cover. So, there is no significant difference overall from the intermediate densities found in the control (untreated) areas.

We were able to calculate rates of change in shrub population characteristics for grubbed and control quadrats. There was no significant difference in the rate of change—mean change in cover—between control and removal areas for any of the three species with sufficient sample size to analyse (tarbush, wolfberry, and the perennial grass, bush muhly).

However, gap data suggest that the two removal and control areas are both structurally and functionally very different, despite relatively minor differences in shrub cover. The area covered by large (>50 cm) canopy and basal gaps was lower in the removal plots despite the fact that bare ground was similar in the control ($49.8 \pm 1.9\%$) and removal ($44.6 \pm 5.4\%$) areas. This is probably due to higher grass canopy cover present on the line transects used to measure gaps in the removal plots than in the control plots; grass clumps tend to be smaller and, therefore, more numerous than shrubs, resulting in smaller basal and canopy interspaces. The ratio of basal area to canopy area is also higher for grasses, further reducing basal gap size. Finally, species differences also contributed. The control plots tended to have more bush muhly, while the removal plots were dominated by tobosa (Fig. 3). Bush muhly is more often found growing underneath shrubs, while tobosa grass tends to occupy the intershrub spaces.

The differences in gap size distribution have significant implications for runoff and erosion (Herrick et al., 2002). Larger canopy gaps leave disturbed soil more susceptible to wind erosion, while larger gaps between plant bases generally reflect shorter runoff path lengths, as obstructions to flow are less frequent. This tends to result in reduced infiltration and increased runoff, with more energy available for water erosion.

Creosote demonstrated similar responses to those of tarbush. Individual shrubs in removal areas were larger on average (in individual shrub cover, volume, and height) after 60-plus years of recovery. Densities were significantly higher in the control areas, however. Thus total cover was (slightly) higher in control strips but total volume did not differ significantly. We also found more individuals of other species in the control areas than in treated areas, suggesting that other woody species have not recovered to former densities. For both tarbush and creosote then, it appears that individual shrubs are capable of reaching large sizes within the time periods spanned by these observations and that this plasticity of growth rates can lead to a substantial recovery of stand volume (and presumably biomass).

The response of grass to the removal of shrubs in this experiment was not straightforward, probably because grass is strongly affected by climate conditions. This was recognized by Jornada scientists in the 1930s—"In depleted condition, following a drought, the plant cover may fall as low as 10% of the soil surface with the tarbush making as much as 70% of the stand. In good condition, the plant cover may occupy 30% or more of the soil surface with little increase in the tarbush stand. The greater density under such conditions is principally grasses" (Jornada Experimental Range, 1941). The dynamic nature of grass cover, the fact that the shrub removal plots were not maintained, and the substantial pretreatment differences in grass cover between treatment and control quadrats, all combine to make it very difficult to come to any conclusions on grass response.

Based on available data (tarbush) and imagery (tarbush and creosote), both treatment areas were in shrub-dominated vegetation states (Bestelmeyer et al., 2003) in 1937 and had returned to those states by 2001 (Fig. 3). The results of this study further illustrate that these shrub-dominated plant communities are extremely resilient based on the fact that they both recovered in less than 65 years following complete removal of the dominant structural and functional group.

The failure of grasses to dominate these two areas following shrub removal suggests that there are additional constraints on grass establishment and persistence at these sites. There are at least five possibilities. One is the lack of grass propagules. This explanation can be rejected for the tarbush site, at least, based on 1937 data and photographs. The presence of grass plants at the creosote site suggests that propagules have probably not been a significant constraint there either. A second hypothesis is that there was significant soil loss prior to and/or following shrub establishment with corresponding declines in soil fertility and soil water availability. Cesium data reported by Ritchie et al. (2003) show that soils at the tarbush site are extremely stable, probably due to the presence of microbiotic crusts. Soil loss is, however, a possible factor at the more highly erodible and steeply sloping creosote site. A third possibility is that either soil structural degradation or change in vegetation structure resulted in a persistent change in hydrology at these sites, limiting grass establishment. This explanation could easily explain the lack of grass establishment at the tarbush site, where water infiltration capacity in grass patches is dramatically higher than in the interspaces (Devine et al., 1998) and under grasses than under tarbush shrubs (Herrick et al., unpublished data). The relatively shallow-rooted grasses (Gibbens and Lenz, 2001) rely on moisture from relatively high intensity summer storms, while the deeper-rooted shrubs can tap into water that is recharged during lower intensity winter storms.

A fourth possibility is the relatively high abundance of rodents and rabbits on shrubland sites compared to grassland sites in the Jornada Basin (Whitford, 1997). The consequences of these animals as both granivores and graminivores for suppression of perennial grass establishment or survival in the shrub-dominated states is substantial (Kerley and Whitford, 2000). A fifth possibility is the landscape spatial context of these treatments (Peters et al., in review). These treatments were applied to plots located within larger areas dominated by these shrubs. Feedbacks from interactions among processes occurring within these plots certainly affect resulting vegetation dynamics. However, neighborhood processes in the surroundings of these plots may modify or overwhelm any localized responses to these treatments within these plots. For example, offsite erosional processes occurring across the landscape and above these plots may certainly influence nutrient and water availability irrespective of plot effects due to shrub removal. Small spatial scale treatments in these arid environments may have little opportunity for long-lasting impacts given landscape scale spatial effects.

5. Conclusions

Historic rangeland remediation treatments conducted in the Jornada Basin of southern New Mexico in the late 1930s were reexamined and remeasured, allowing valuable insight into response of tarbush and creosote (individuals and populations) to an extreme disturbance. Individual shrubs in removal (grubbed) areas were larger than in control areas on average (in individual shrub cover, volume, and/or height) after 60 plus years of recovery. Shrub density, however, was significantly higher in the control areas. The total shrub cover was (slightly) higher in control strips, but total shrub volume did not differ significantly between controls and treatments after more than 60 years. The fact that population density does not recover to the same level as untreated areas suggests that recruitment events may be relatively rare. Conditions suitable for establishment of new individuals may be encountered only infrequently, a pattern often described for other arid shrublands.

These shrubland ecological sites are strongly influenced by a single shrub species, the dominance of those shrub populations is very long lasting, and transitions away from a degraded shrub-dominated state are unlikely. A transition towards a more desired herbaceous-dominated plant community requires inputs, often expensive, that must overcome certain critical constraints, such as soil structure degradation, which plague these sites. When these multi-equilibrial sites are in degraded states, the removal of the dominant shrub is not sufficient to eliminate the constraints which reinforce the shrub-dominated state. Remediation of these sites requires additional measures.

Nevertheless, the historical datasets and the ability to relocate field plots provide us with unique opportunities to understand the long-term dynamics of these arid systems. Woody plant populations demonstrate a high degree of resilience (ability to recover after a severe perturbation) reflected in the recovery of total cover to pretreatment or, in some cases, control levels. Individual plants in removal areas have grown to larger sizes than plants in the (higher density) controls, suggesting that density dependence or interference limits plant size in these arid shrub populations. Finally, the continued increase in shrub cover in control areas since the 1930s (in the tarbush site) suggests that shrub populations had not reached any equilibrium at that time. All of these insights would have been difficult or impossible to gain from short-term experiments or studies initiated more recently; we owe much to the original scientists and the CCC work crews who initiated these studies, as well as to the aerial photography and historical documentation efforts that allowed relocation and resampling.

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