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Experimental Treatments for Increasing Perennial Grass Cover in a Shrub-Invaded Grassland in the Southwestern Borderlands Region of Arizona and New Mexico

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Abstract

The density of mesquite (*Prosopis* spp.) and other woody species has increased on desert and semidesert grasslands in the southwestern United States. This increase in woody species has been associated with the decline of native herbaceous plants and a loss of biological diversity and productivity. There have been numerous attempts to reverse this situation. The effort reported here employed crushing the woody species with heavy equipment, with and without seeding native perennial grasses, and the use of prescribed fire. The treatments were not expected to kill the woody species but to reduce their dominance on the rangeland. The mechanical treatments significantly reduced the cover of woody plants compared to the untreated control plots on two ranchland sites and the effect lasted 9 years. On these ranches, perennial grass cover, particularly plains bristlegrass (*Setaria macrostachys*), and production were higher on crush + seed treatments for 2 or 3 consecutive years until the severe drought of 2003 negated the treatment effects. On pasture at a third site, woody cover was lower on treated plots compared to the control plots. The seeded and residual grass cover was not sufficient to carry the prescribed fires without supplemental ignitions. Though the fires initially reduced the crown cover of woody species on the treated plots, most recovered within 3 years. The treatments were not successful under severe drought conditions. A test under wetter conditions or with a more drought-tolerant mix of seeded grasses might produce different results. Continued, periodic fire treatments might reduce woody plant cover and competition with the grass stand. Additional fire treatments should be attempted in any future experiments.

Keywords: semidesert grasslands, mechanical treatments, woody species, seeding native perennial grasses, prescribed burning, climate, southeastern Arizona, southwestern New Mexico.

Cover: Fire crews conducting prescribed burns. (USDA Forest Service)

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Contents

INTRODUCTION

The density of mesquite (*Prosopis* spp.) and other woody species has been increasing in the grasslands of the U.S. Southwest since the end of the 19th century. The increased cover of woody plants has resulted in a decline of native herbaceous plants and a loss of site productivity and biological diversity (Branson 1985; Brown and Archer 1989; Dahl et al. 1978; Grover and Musick 1990; Martin 1975; Ruyle et al. 1988). These changes have been linked to the overgrazing that followed the purchases of large tracts of land by corporations, especially after the completion of the transcontinental railroad (Sheridan and Hadley 1994), and, later, to aggressive fire control by land management agencies. The increase in woody species has also been attributed to changes in the climate (Grover and Musick 1990). Prior to 1890, fires that were started by lightning or by Native American people were carried by the herbaceous cover, reducing the density of shrub and tree regeneration and of larger individual plants. A study in south Texas indicated that 90 percent of the mesquite clusters on the landscape were less than 100 years old (Archer 1989). A common opinion is that the trend of increased shrub dominance in the grasslands will not diminish (Wilson et al. 2001).

Private and public land managers are attempting to reverse this trend by using mechanical, chemical, and prescribed fire techniques. The goal is to manage the semidesert grasslands and savannas according to the concepts of ecosystem management with an emphasis on sustaining and, where needed, restoring ecological function and production to the entire ecosystem. It is anticipated that the resulting increase in productivity will help support the local ranching economy, decrease erosion, protect open spaces, and improve the biological diversity of the landscape. Modern range management techniques are expected to avoid the effects of previous overgrazing of vegetation in the Southwest.

Several research studies have examined the interactions of livestock grazing and prescribed fire on summer and winter annual and perennial vegetation. The knowledge would help managers develop methods to increase site productivity and vegetation diversity. Valone and Kelt (1999), working near the study area in this report, found significant differences in species abundance related to the burn treatments or the grazing treatments. However, the two disturbances acted independently. They determined that fire did not have an effect on nonshrub species. Drewa and Havstad (2001) also examined the influence of fire and grazing in a range where mesquite was present. They found that the presence of mesquite did not affect the response of nonshrub species. Perennial grass cover decreased in burned plots and increased in nonburned plots. Grazing also resulted in a decrease in perennial grass cover. This study also reported that grazing and burning act independently on the plants sampled.

These studies did not evaluate the impacts of mechanical range restoration treatments and fire on the understory flora and overstory woody vegetation. Historical revegetation research in desert grasslands has shown the necessity of modifying the seedbed to catch and retain precipitation in order to increase the successful establishment of seeded grasses (Roundy and Biedenbender 1995). The USDA Forest Service (hereafter, Forest Service), Rocky Mountain Research Station, the USDA Natural Resources Conservation Service (NRCS), and their cooperators established an experiment to determine whether treatments that crushed the shrubs with or without seeding native perennial grasses would increase native herbaceous plant cover and productivity. Both types of treatments included prescribed burning after the grasses became established in a further attempt to control the dominant cover of trees and shrubs on the land. The study was established in 1996 on three privately owned rangeland sites in Arizona and New Mexico within the area known as the Southwestern Borderlands region. Treatments were conducted in 1999, followed by prescribed burning in 2005.

The Semidesert Grasslands

Southwestern semidesert grass-shrub rangelands occupy the Southwestern Borderlands region, a strip of land from 50 to 100 miles wide along the southern borders of Arizona, New Mexico, and west Texas (Martin 1975). In southeastern Arizona and central Arizona, desert grassland ecosystems cover approximately 15 million acres (McClaran and Brady 1994). This vegetation type is common throughout the Malpai Borderlands area, which covers about 802,750 acres in the San Bernardino Valley (Arizona), southern San Simon Valley (Arizona and New Mexico), and Animas Valley (New Mexico). The terrain in the valleys, each bordered by local mountain ranges, is generally flat.

These grasslands are found between 3,000 and 6,000 feet in elevation, where annual precipitation varies from 8 to 20 inches. Southeastern Arizona and southwestern New Mexico receive precipitation during two periods. The winter rains generally develop from frontal storms originating in the Pacific Ocean. Summer moisture occurs during the summer monsoon period, which officially runs from June 15 to September 30. The monsoons can account for 45 to 75 percent or more of the annual precipitation and most herbaceous plant growth occurs during this season. Ninety percent of grass growth, for example, occurs from July through September (McClaran 1995). Perennial grass production in the semidesert grasslands depends on the current summer rainfall and the previous summer rainfall (Cable 1975).

Drought is an integral part of the region's climate. Arizona, particularly southeastern Arizona, and southwestern New Mexico have been in a drought that began in 1999 and continued through the end of the study (2007). The National Weather Service's calculations of the Palmer Drought Severity Index, using temperature and precipitation in a formula to determine dryness, indicated summer drought conditions throughout most of the area during the study. The Palmer Drought Severity Index for the 60 warm-season months (May through October) from 1999 through 2007 indicate that the Arizona portion of the region, which includes Cochise County, had 40 percent of the months in the extreme or severe drought categories and 15 percent in the moderate drought category (NOAA NCEI 2019b). Twenty-two percent of the months in the New Mexico portion of the region, which includes Hidalgo County, also were in the extreme or severe drought categories and 10 percent were in the moderate drought category.

Mesquite has always been a component of the semidesert grasslands. There are three species of mesquite and two subspecies in the Southwest (Wilson et al. 2001). According to Wilson and others (2001), the mesquite in the Borderlands region can be either *Prosopis glandulosa* var. *glandulosa* or *P. glandulosa* var. *torreyana*. Early travelers reported dense stands of mesquite along stream channels and at the base of neighboring mountains in the 1840s. Other travelers in the mid-1800s reported that some bottomland near Tucson and lands in the San Simon Valley, Arizona, were covered with good stands of grass with a few scattered trees (Cox et al. 1983). The increase in mesquite has been documented by repeated photography by Hastings and Turner (1965) and by Turner and others (2003). Research in the Jornada Experimental Range in central New Mexico determined that the frequency percentage of the mesquite canopy in a grassland increased 10-fold between 1935 and 1980 (Hennessy et al. 1983). One estimate is that livestock carrying capacity dropped from 12 to 14 head per section to about 4 head per section because of increased woody plant dominance. Warren and others (1996) report that mesquite canopy covers below 17 percent appear to have little effect on forage production. Ansley and others (2013) indicate that woody cover should be kept below 30 percent to maintain productive grass cover of C_4 (warm-season) mid-grasses such as sideoats grama (*Bouteloua curtipendula*). Mesquite is a long-lived and drought-tolerant genus. Whatever the causes for the increase in mesquite and other woody species, established mesquite tends to thicken whether the range is grazed or not (Vallentine 1980).

Land managers are attempting to reduce the trees and shrubs in the Borderlands by using a number of methods, including machine and hand grubbing, herbicides, cabling and chaining, root plowing, and prescribed fires (Martin 1975; Wilson et al. 2011). Grass responses to control efforts are excellent in moderate to dense stands of trees and shrubs where there is more than 6 to 8 inches of warm-season precipitation and a satisfactory remnant of perennial grasses existed. However, mesquite, which has buds on its roots, sprouts vigorously after the tops are killed and, unless the roots are removed from the soil, treatment effects may be short lived. In one mechanical treatment, in the San Simon Valley, trees had recovered to their former size and density within 4 years (Jordan and Maynard 1970).

Fire was a natural part of the semidesert grassland ecosystem before settlement, and land managers are attempting to reestablish its role. The impact on shrubs and trees of wildfires and prescribed fires depends on fire intensity. Mid-grass communities may benefit from periodic burning; for example, communities dominated by sideoats grama, plains lovegrass (*Eragrostis intermedia*), and tanglehead (*Heteropogon contortus*) declined in the absence of fire, especially during short regional droughts. Increased fire frequencies appear to favor the nonnative Lehmann lovegrass (*E. lehmanniana*) in the Fort Huachuca area of southern Arizona (Robinett and Barker 1996). Observed frequency of this lovegrass species increased 9 percent in an area receiving one fire between 1977 and 1992 and 96 percent in an area with five fires during the same period (Robinett 1994). The increases were at the expense of sideoats grama, black grama (*B. eriopoda*), and plains lovegrass. However, Lehmann lovegrass does not appear to alter the fire regime to the detriment of native plants that are tolerant of high fire temperatures (McDonald and McPherson 2011) at elevations up to approximately 5,000 feet, depending on aspect and local microclimatic conditions (J.R. Bemis, personal correspondence, 2020). Lehmann lovegrass-dominated grasslands may be more capable of carrying fire than areas dominated by native species (Robinett 1994).

Pase and Granfelt (1977) considered it optimistic to assume that fire can solve the woody plant problem. Fires would have to be ignited in areas where adequate grass cover exists to carry the fire. Hot fires can kill grass plants as well as trees and shrubs. Pase and Granfelt

(1977) recommended fire intervals of greater than 5 years so that herbaceous plants have time to recover and set seeds. Two high-precipitation seasons may be necessary to obtain sufficient fuel loadings for natural fires on desert grasslands (W.H. Kruse, personal conversation, 1999). Even hot fires may have only temporary effects. A June wildfire on the Santa Rita Experimental Range south of Tucson killed 30 percent and damaged 65 percent of the mesquite (*P. velutina*), but overall tree stocking was reduced by only 10 percent because of sprouting (DeBano et al. 1996). Mesquite also is a prolific seed producer and seeds are viable for long periods.

Although fire alone may be insufficient to control mesquite, it does provide long-term ecological benefits to these grasslands. In addition to controlling some of the mesquite, fires remove dead mesquite parts and excessive accumulations of grass litter. Observations at Fort Huachuca indicated that the aboveground development of mesquite sprouts was retarded in an area with repeated fires even though the sprouts originated from relatively large trees.

OBJECTIVES

The general objective of this study was to determine whether the shrub and tree component of the Borderlands ecosystem can be managed for ecological and economic benefits of the landscape. Improved composition and density of native perennial grasses and reduced influence of mesquite and other woody species were the immediate objective. The complete eradication of mesquite is not a feasible goal.

The specific goal was to evaluate the effects of mechanically crushing mesquite and other woody species to determine whether simultaneous seeding of native perennial grasses, followed by prescribed fire, would decrease woody plant survival and increase recovery of grass and forb cover. The use of herbaceous cover, enhanced by seeding, to carry a fire is a major improvement over earlier efforts to reduce mesquite cover in the San Simon watershed without fire or herbicide treatments. Fire is a vital component of the study because of mesquite's ability to sprout from root buds. Prescribed fire would also be expected to further degrade the health of surviving trees and shrubs and reduce the health of woody plant sprouts. The study also could provide insight into how the native and seeded semidesert grassland plants were responding to a relatively long period of extreme drought. The impacts of the treatments on herbaceous vegetation, woody species, and soil surface characteristics over the study period would be evaluated.

HYPOTHESIS

The core hypothesis of this study was that treating a brush-dominated semidesert grassland by mechanical crushing and crushing with seeding of native perennial grass species, with subsequent prescribed burning of the grass stands in both treatments, would have the following results: 1) increased grass cover, 2) reduced cover of bare soil, and 3) reduced influence of woody shrubs relative to the untreated plots. The ability of prescribed fires to affect tree dominance was of particular interest. Repeated fire treatments may be necessary to reduce woody plant recovery but were not attempted here.

METHODS

Plot Design

The experiment was conducted in cooperation with three private land owners within the Malpai Borderlands area in southeastern Arizona and southwestern New Mexico (fig. 1). The three sites provide a gradient of elevations from 3,840 to 4,780 feet. The Malpai Ranch, located in the San Bernardino Valley, east of Douglas, Arizona and along the Geronimo Trail Road (Cochise County), is at 3,840 to 3,860 feet in elevation. The Roos Ranch (Hidalgo County) is 1 mile north of Rodeo, New Mexico and east of Arizona-New Mexico Highway 80. The elevations range from 4,120 feet to 4,150 feet. The George Wright pasture (Hidalgo County) is on the Diamond A Ranch, south of Animas, New Mexico and west of New Mexico Highway 338. Elevations are between 4,740 and 4,780 feet. An associated study, on the Sycamore Ranch (fig. 1), attempted to use intensive livestock grazing as a site preparation tool for reestablishing perennial grasses on a sensitive archaeological site (Gilman 1999). However, these results are not reported here.

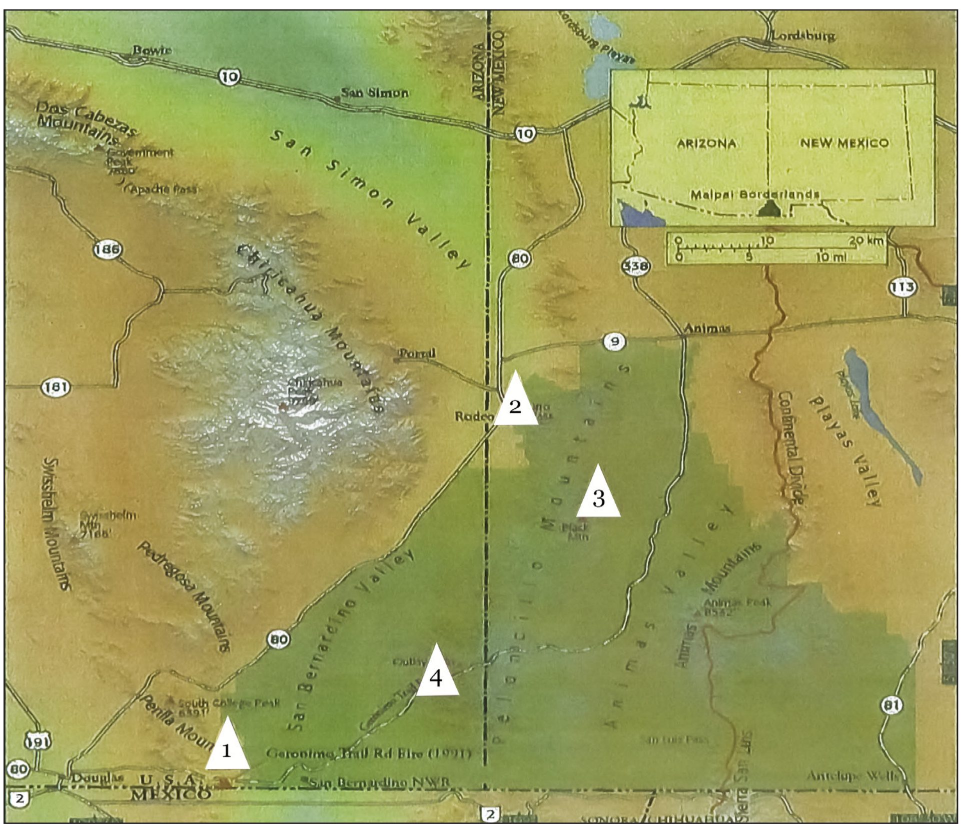


Figure 1—Locations of the Malpai Ranch (1), Roos Ranch (2), George Wright pasture (3), and Sycamore Ranch (4) research sites within the Malpai Borderlands region of Arizona and New Mexico. The Malpai Borderlands region (darker green) covers approximately 803,000 acres.

Each site contains 12 treatment plots that are contiguous with each other. Each treatment was replicated four times and the treatments were randomly assigned to the plots. This arrangement was intended to moderate any soil differences between plots. The individual plots are squares 500 feet on a side that cover 5.75 acres. At the Malpai site, the plots are arranged in a rectangle 2,000 feet long and 1,500 feet wide (fig. 2). The Roos and George Wright plots each are laid out as two adjoining rectangles 3,000 feet by 500 feet with six plots in each rectangle. A barbed-wire fence was constructed around the perimeter of each 69-acre research site following the mechanical treatments to control grazing by cattle.

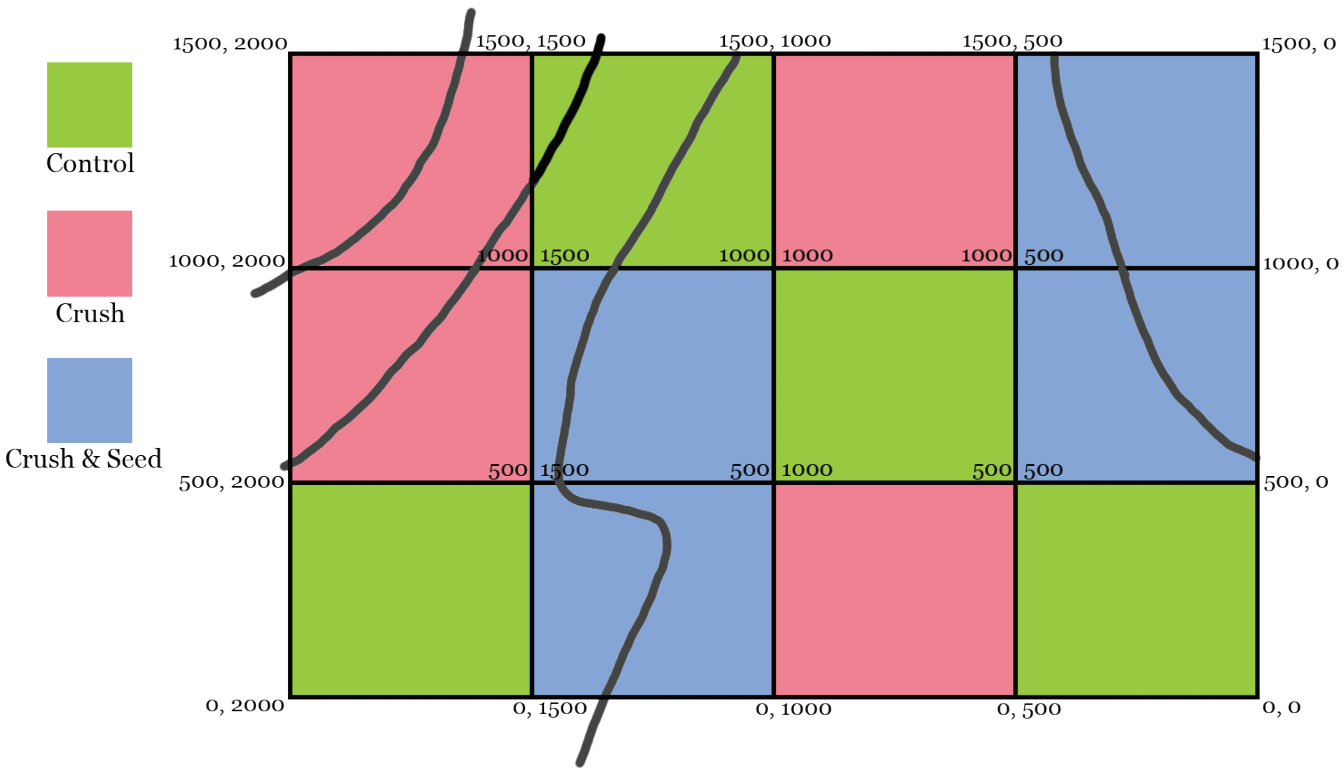


Figure 2—Map of the study site layout at the Malpai Ranch showing treatment locations and soil characteristics: 1 = Baboquivari-Combate complex; 1190 = Outlaw-Epitaph-Paramore complex; 1235 = Eloma-Caralampi-White House complex; 1305 = Elgin-Outlaw complex. The other numbers identify photo points.

Treatments

The treatments on the three sites reported here were:

1. Crushing the woody species with a Marden Brush Crusher (Marden Industries, Florida) drawn by a TD-25 crawler tractor (International Harvester, Illinois), and subsequent use of prescribed fire (crush + burned).
2. Crushing the woody species with a Marden Brush Crusher and simultaneously seeding native perennial grass species from a rangeland drill attached to the frame of the rear drum of the crusher (fig. 3), and subsequent use of prescribed fire (crush + seed + burned).
3. Control with no mechanical treatments, seeding, or prescribed fire.

Figure 3—Marden Brush Crusher and rangeland drill being pulled by a TD-25 at the George Wright pasture site.

The only exceptions to the random assignment of treatments were at the Roos Ranch, where a potential archaeological site was designated as a control plot, and at the George Wright pasture, where a control plot was designated because it contained a Federally listed cactus species, *Coryphantha scheeri* var. *scheeri*. The same three rangeland treatments were repeated at each ranch. Initially, the plan was to combine the results for analyses. However, it soon became apparent that the sites were different enough from each other because of elevation and soil characteristics that it would be difficult to combine data; instead, it would be better to analyze each site independently. Another reason for analyzing each site separately was that the mix of native perennial grass seed was customized for each ranch by the NRCS. The plots were mechanically treated in 1999. Vegetation measurements were conducted in 1996 prior to treatment and every year from 1999 through 2007.

The Marden Brush Crusher has the benefit that it chops woody material into small chunks, incorporates material into the upper soil layers, creates shallow indentations in the soil to catch seed and precipitation, and does not rip and bring any underlying clay substrates to the surface. A tractor speed of 9 to 10 miles per hour produced satisfactory depressions in the soil, resulting in deeper grooves, a better job of chopping woody species into 18-inch pieces, and fewer problems of balled-up seed. The attached drill was calibrated to drop approximately 23 seeds per square foot. Some of the larger mesquites and other woody trees were flagged before treatment for retention and not crushed to create a savanna-like appearance. The U.S. Department of the Interior Fish and Wildlife Service's San Bernardino National Wildlife Refuge and the Douglas Ranger District, Coronado National Forest, supported the research by transporting equipment and water for the Marden Brush Crusher to the study sites.

Prescribed burning of all but the control plots occurred at the Roos and George Wright sites on June 8, 2005 and at the Malpai site on June 20 and 21, 2005. The burning was started at the Malpai site on June 20 but halted because of an approaching lightning storm and resumed the next day. Burning was conducted by the Douglas Ranger District fire crew of the Coronado National Forest. The original plan was to ignite the grass and let the fire burn into the woody species. However, because the grass cover was spotty on most plots, some trees were ignited individually. A total of 64 trees and shrubs (8 plants per plot) were initially selected in the treated plots on each site and permanently marked for monitoring. In addition, 32 trees and shrubs were marked and monitored in the control plots.

Weather Data

Precipitation and temperature are major factors influencing vegetation growth and development. At each site a weather station was set up to measure precipitation, temperature, relative humidity, and wind direction and wind speed. Weather stations were established at the Malpai, the Roos, and the Wright sites in June 1999. Each station was usually visited monthly and the data, which were stored electronically in a computer within the weather shelter, were downloaded into a laptop computer. Data were subsequently transferred to the computers at the Forest Service's Forest Sciences Laboratory in Flagstaff, Arizona to be checked and summarized.

Site Descriptions

Malpai Site

The Malpai Ranch is on land that was part of the ranch owned and operated by pioneer cattleman and Tombstone, Arizona sheriff John H. Slaughter (Erwin 1965). Several early travelers in the 1840s described the area as having water and rich, abundant grama grass. The area was not heavily grazed before the mid-1880s (Erwin 1965).

The initial vegetation of the Malpai site consisted of stands of woody species including mesquite, American tarwort or tarbush (*Flourensia cernua*), and whitethorn (*Acacia constricta*) with little grass cover (fig. 4A). The pretreatment survey of the Malpai site in 1996 indicated that the average cover of bare soil (sampling standard errors reported in parentheses) was 54.1 (3.2) percent of the land surface, and woody species cover was 22.1 (1.9) percent. Average cover by species on the 12 plots was mesquite, 9.0 (1.9) percent; whitethorn, 8.0 (1.6) percent; and tarwort, 4.3 (1.4) percent. These species accounted for 30 percent, 47 percent, and 23 percent, respectively, of the trees and shrubs sampled and marked prior to the prescribed burn. Some other common species identified within the site before treatment were three-awn grass (*Aristida* spp.), bush muhly (*Muhlenbergia porteri*), broom snakeweed (*Gutierrezia sarothrae*), tobosagrass (*Pleuraphis mutica*), vine mesquite grass (*Panicum obtusum*), and assorted annual grasses and forbs. The average foliar cover of perennial grass species on the 12 plots was 8.9 (2.2) percent (Sundt 2007; Traphagen 2001, 2008).

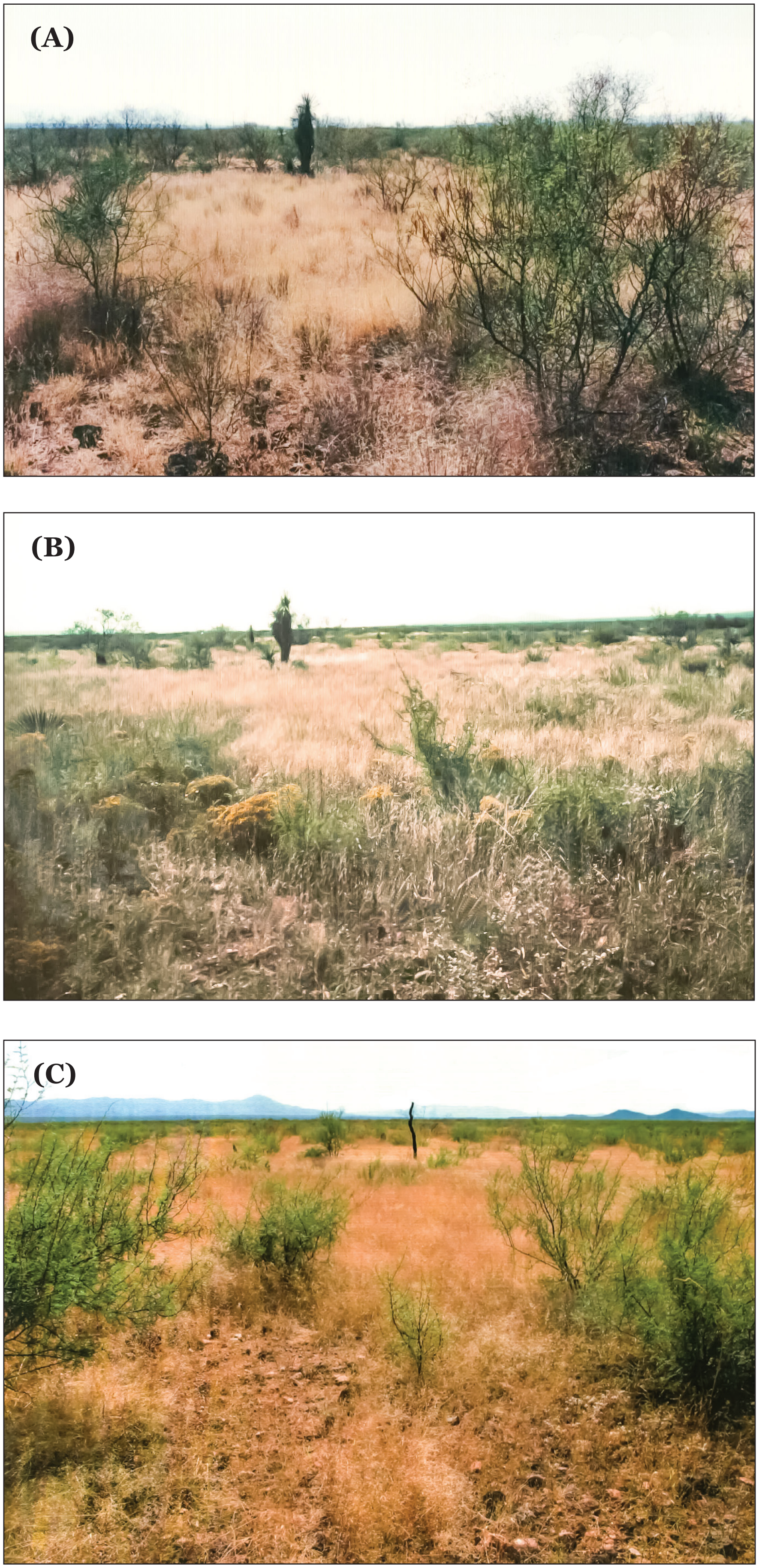


Figure 4—Series of photographs from the same location in southeastern Arizona in 1996 before treatment (A), in 1999 immediately after treatment (B), and in 2006 (C) (photos by Peter Sundt, used with permission).

Soils

The survey for the Malpai site (fig. 2) indicates that soils belong to the Eloma-Caralampi-White House Complex (Eloma is a thermic Ustic Haplargid), Baboquivari-Combate Complex (Combate is a thermic Ustic Torrifluvent), Elgin-Outlaw Complex (Elgin is a thermic Calcic Paleargid), and the Outlaw-Epitaph-Paramore Complex (Outlaw is a thermic Typic Calcitorrert) (Breckenfeld 1997). The Eloma-Caralampi-White House Complex and Elgin-Outlaw Complex are the most common soils. Sandy loam surface soils with lower horizons of clay are common throughout the site. Gravels and cobbles cover part of the soil surfaces within the plots. These soils are derived from mixed fan alluvium.

Roos Site

The Roos research site is on private ranchland at the foot of the west side of the Peloncillo Mountains. The topography is relatively flat except for several generally shallow drainages that originate in the Peloncillo Mountains and cross the research area from east to west. Prior to treatment the average cover of mesquite was 9.4 (1.6) percent and bare soil covered 35.4 (3.5) percent. Mesquite was the primary woody species on the Roos site where tarwort and whitethorn were absent or rare (Sundt 2007; Traphagen 2001, 2008).

Soils

The NRCS soil survey (Breckenfeld 1997) classified four bands of soils on the Roos site. Soils have been classified as belonging to the Mohave soils and to the Hayhook-Bucklebar and Arizo-Riverwash Complexes. The Hayhook-Bucklebar soil covers about 6.5 plots and is a Typic Haplargid; the Arizo soil is a Torriorthent. The soils on the Roos site are generally characteristic of basin floors, are of mixed parent material, and are relatively deep and well drained.

George Wright Site

The site on the George Wright pasture occurs at the highest elevation of the three study sites, ranging from 4,740 to 4,780 ft. The pretreatment inventory in 1996 indicates that the mesquite cover was 15.0 (1.8) percent and the cover of bare soil was 58.1 (2.0) percent. As with the Roos site, mesquite was the primary woody species where tarwort and whitethorn were absent or rare. Other common plants were three-awn grass, croton (*Croton corybulosus*), vine mesquite grass, and broom snakeweed. Average perennial grass cover on the site was 10.7 (2.0) percent but varied among the plots (Sundt 2007; Traphagen 2001, 2008).

Soils

The NRCS soil survey (Breckenfeld 1997) classified the soils as Forrest sandy loam, 0 to 3 percent and Libby sandy loam, 0 to 2 percent. The Forrest soil mainly occurs in the northern and eastern part of the site while a band of Libby soils crosses through the center of the site. The Forrest soil is of mixed parent material, contains less than 5 percent rock fragments, and is classified as very deep. The Libby soil is of mixed origin, contains 35 percent or less of rock fragments, and is classifed as very deep. The ecological site for both soils is sandy loam upland.

Treatment History

Treatments began on February 6, 1999. At the Malpai site, the customized species mix determined by the NRCS was galleta grass (*Pleuraphis* spp.), sideoats grama, blue grama (*Bouteloua gracilis*), and plains bristlegrass (*Setaria vulpiseta*). A small amount of fourwing saltbush (*Atriplex canescens*) was included. The seeding rates for the crush + seed + burned plots, in pounds per acre, were: galleta grass, 9.6; sideoats grama, 4.5; blue grama, 1.3; plains bristlegrass, 4.4; and fourwing salt-bush, 1.3. A series of photographs was taken from the same point in a crush + seed plot to show changes in cover over time from 1996 (pretreatment), 1999 (posttreatment), and 2006 (figs. 4A–C). Progress was delayed at the Malpai and Roos sites throughout the treatments because of repeated breakdowns of the TD-25, the Marden Brush Crusher, or the drill.

The equipment was moved to the Roos Ranch on February 11, 1999 and the site was finished on February 26, 1999. The species mix was Arizona cottontop (*Digitaria californica*), sand dropseed (*Sporobolus cryptandrus*), blue grama, plains bristlegrass, and sideoats grama. The seeding rates, in pounds per acre, were: Arizona cottontop, 0.4; sand dropseed, 2; blue grama, 1; plains bristlegrass, 4.4; and sideoats grama 4.6. Two relatively short incised channel sections in the eastern parts of two plots (a control plot and a crush + seed plot) were not treated by the mechanical equipment.

Treatments began at the George Wright site on March 1,1999 and were completed by March 3, 1999. The site was seeded with sideoats grama, blue grama, plains bristlegrass, plains lovegrass, and cane bluestem (*Bothriochioa barbinodis*). The seeding rates, in pounds per acre, were: sideoats grama, 6.1; blue grama, 3.5; plains bristlegrass, 8.7; plains lovegrass, 0.2; and cane bluestem, 0.2. The plains lovegrass, cane bluestem, and some Arizona cottontop were seeded with a hand cyclone seeder. The small seed size made it difficult to seed with the rangeland drill.

Measurements

Vegetation

Measurements were made to determine the cover of rock (greater than 0.5 inch in diameter), bare ground, soil, litter, and the foliar cover of all live plant species (Sundt 2002). These were measured using the line-point intercept method (Elzinga et al. 1998). Ten transects were systematically established in each plot and 100 points were sampled along each transect using a steel pin to mark a point to identify the plant or soil category, for a total of 1,000 points in each plot. Transect data were kept separate to estimate within-plot variance. The surveys were conducted before treatments in 1996 and for 9 years (1999 through 2007) afterwards. An analysis of the statistical power and limitations of the method using data from this study was published (Sundt 2002). Repeat photographs were taken at permanent locations during most surveys to document changes in vegetation. Woody species in this study were trees, shrubs, and subshrubs, including mesquite, whitethorn, tarwort, broom snakeweed, burroweed (*Isocoma tenuisecta*), catclaw mimosa (*Mimosa aculeaticarpa* var. *biuncifera*), soaptree yucca (*Yucca elata*), and fourwing saltbush. A list of all plant species identified on the four restoration sites (including the Sycamore Ranch) is found in the Appendix based on information collected by Sundt (2007) and Traphagen (2007) and with nomenclature confirmed in the PLANTS Database (USDA NRCS 2019).

Perennial grass production, composition, and total annual production were determined within each plot using a double sampling protocol along a line transect (Traphagen 2001, 2008) based on the research by Pechanec and Pickford (1937) and Ahmed and others (1983). Annual perennial plant production and total annual production were determined on a 500-foot transect containing ten 9.84-square-foot quadrats. The transect was placed in the center of the plot. There was a buffer around each quadrat. Measurements included herbaceous and nonwoody shrub cover. To take into account "interspersion" (Elzinga et al. 2009), it would have been ideal to have several transects in each subplot; however, the expense and time required to measure additional quadrats in 36 subplots prevented the increase in measurement. Two out of 10 quadrats were randomly selected and clipped, and the material dried. The resulting relationship between green and dry weights was used to estimate values for the other eight plots. Plant material on average was 90 percent dry weight. Production surveys were conducted in 2000 through 2007.

Prescribed Burning

In preparation for the prescribed burning treatment, two trees or woody shrubs (mesquite, whitethorn, or tarwort) were selected around each of four randomly located points in each plot, including the four control plots on each site, for a total of eight trees per subplot. There were 64 trees or shrubs in treated subplots and 32 in control subplots. Each tree or shrub was marked with an aluminum pin, and height and two measurements of crown diameter were taken. The geometric mean crown diameter was used to calculate crown area. Measurements were taken in 2005 before burning and in 2006 and 2008. The burning operations did not impact all marked trees in the plots designated for burning. The 2006 inventory recorded the percentage of crown damage on surviving trees. The categories were: no fire damage, more than 75 percent of the crown consumed, 25 to 74 percent of the crown consumed, and minor damage with less than 25 percent of the crown consumed. Trees in the eight treated plots on each site were divided into categories based on whether the tree was burned in the prescribed fires. The categories were: crush + seed + burned, crush + seed + unburned, crush + burned, crush + unburned, and control. The 32 trees and shrubs in the control plots were also measured for crown and height characteristics in 2005 and 2008.

Weather Records

Some monthly weather records are incomplete because of lightning strikes near the gauge, computer problems, or other difficulties. The missing monthly records were estimated by using regressions between the site and a neighboring station. The Malpai site weather station was paired with the weather station at the San Bernardino National Wildlife Refuge, which is about 2 miles south of the research site. Records from both the Roos and George Wright sites were paired with the weather station maintained by the Bioresearch Ranch (Moir 2011) in Post Office Canyon on the northwestern side of the Peloncillo Mountains, southeast of the Roos site at 5,170 feet. The Roos gauge is about 7.4 miles from the Bioresearch Ranch location and the Wright gauge is about 11 miles to the east of that location.

Precipitation records were divided into the cool-season period and the warm-season (fig. 5) period, and one regression was prepared for each of the two periods. The warm season is the more important season for herbaceous production in the Southwestern Borderlands (see *The Semidesert Grasslands* section). The information for the research sites was compared to regional drought reports from the National Climatic Data Center (now the National Centers for Environmental Information) of the National Oceanic and Atmospheric Administration (NOAA NCEI 2019b).

Average monthly temperatures between 1999 and 2010, although not tested statistically, appear to be similar across the four sites. The warmest month was July at three sites, with an average of 81.3 °F.

<u>*Malpai Site*</u>

Average annual precipitation (January–December) at the Malpai station was 11.83 (0.88) inches for the 10 years of record (2000–2009) (fig. 6). The driest year in the region during this study was 2003, when 6.10 inches were recorded at the Malpai gauge. The National Climatic Data Center reported that 2003 was the fourth warmest year on record (NOAA NCEI 2019a); Cochise County was in severe or extreme drought throughout the year. The wettest year was 2000, when 15.01 inches were recorded. The averages for the study period were 3.25 (0.68) inches for the cool season (November–April) (not shown) and 8.54 (0.93) inches, or 72 percent of the moisture, for the warm season (May–October) (fig. 5). In 2003, 3.00 inches were recorded in the cool season and 3.46 inches in the warm season. The wettest warm seasons occurred in 2000 and 2006.

The overall average annual temperature for 8 years was 66.0 (0.5) °F. The information for 2007 was not included because of incomplete records. Seven of the warmest average monthly temperatures—for January, May, July, August, September, October, and November—were in 2003. Temperatures greater than 100 °F were recorded at the Malpai site for every month from May through September in 2003.

<u>*Roos Site*</u>

Average annual precipitation at the Roos weather station was 11.94 (0.78) inches for the 10 years of record (fig. 6). The two driest years at this site were consecutive: 2003, when 7.35 inches were recorded, and 2002, when 9.69 inches were recorded. The wettest year was 2000 with 15.45 inches. The average cool-season precipitation was 3.19 (1.6) inches (not shown) and the average warm-season precipitation was 8.68 (0.93) inches. Approximately 73 percent of the average annual precipitation occurred during the warm season. The driest cool season precipitation was in 2006 with 0.55 inch; this followed the wettest cool period, in 2005, with 6.42 inches. The driest warm season was 2003 with 3.50 inches. The wettest warm season was 2000 with 12.90 inches and the second wettest was 2006 with 12.69 inches (fig. 5).

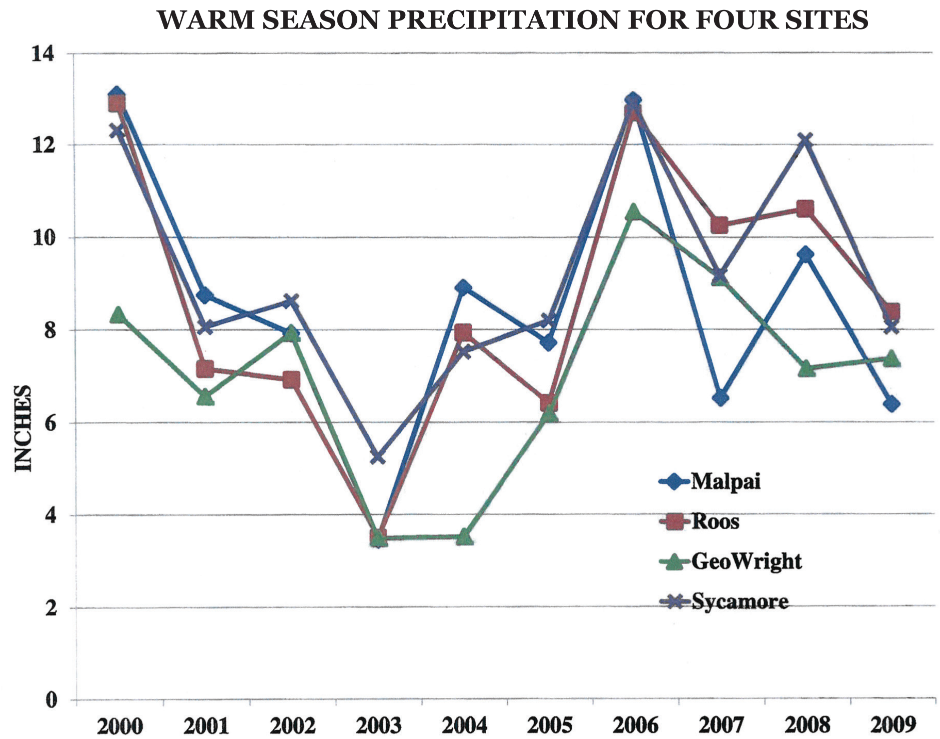


Figure 5—Warm-season (May–October) precipitation for the research sites, by year. Warm-season precipitation is related to monsoon storms, which can result in spotty, but often high- intensity, rainfall over a large area. It is vital for the growth and survival of plants in the semidesert grasslands.

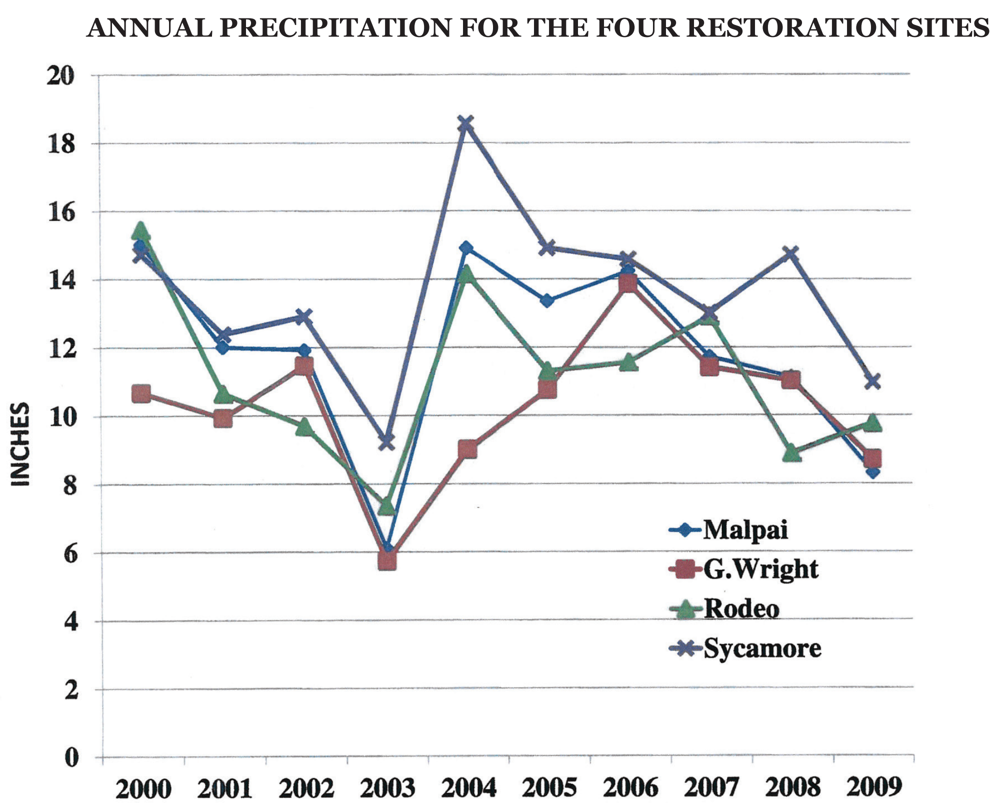


Figure 6—Annual precipitation for the research sites, by year. The first full year of operation for each weather station was 2000.

The average temperature between 2000 and 2009 was 63.0 (0.4) ^{o}F. The warmest year was 2001, with an average annual temperature of 65.4 ^{o}F, and the coolest year was 2008, with an average annual temperature of 60.8 ^{o}F.

George Wright Site

Average annual precipitation at the George Wright site was 10.07 (0.62) inches for the 10 years of record (fig. 6). The driest year at this site was 2003, when 5.72 inches were measured. The second driest year was 2009, when 9.76 inches were measured at this location. The wettest year was 2007, with 12.91 inches. The average cool-season precipitation was 2.92 (0.54) inches and the average warm-season precipitation was 7.02 (0.71) inches (fig. 5). Approximately 71 percent of the annual precipitation occurred during the summer. The driest winter and summer were in 2003, when 2.85 inches and 3.49 inches, respectively, were measured. The wettest warm season was in 2006, with 10.56 inches, and the wettest cool season was 2001, with 4.41 inches.

The average temperature between 2000 and 2009 was 61.6 (1.22) ^{o}F. The warmest year was 2008, with an average annual temperature of 68.6 oF, and the coolest year was 2001, with an average temperature of 57.2 ^{o}F.

Soils

Surveys of the soils on each site (Breckenfeld 1997) were linked to data from previous Arizona or New Mexico soil survey reports. Soils were variable within the individual study sites, for example at the Malpai site (fig. 2), but surface soils were usually similar. Soil differences were not considered in the analyses. It was anticipated that slight differences in surface soils would not influence the success of grass establishment and that the randomization of treatments would moderate any soil influences that might occur.

Vegetation Analyses

Canopy foliar cover fluctuations for the perennial grasses and woody species, and percent cover of bare soil-rock categories for the three treatments and the years of study are presented for each of the study sites. Other species or site characteristics that were affected by the crush and crush + seed treatments are also listed. Not all collected data could be analyzed due to patterns of missing information (for example, empty cells). The GLIMMIX (Generalized Linear Mixed Effects Model) procedure (SAS Institute 2014) was used for responses with adequate data to determine whether differences were significant. Alpha values of 0.05 were used to indicate statistical significance.

The GLIMMIX model used included fixed effects for year, treatment, and year × treatment effects by species or species groups (for example, all woody species grouped together) or physical attributes. Adjustments for random effects of plots and sites were also included in the GLIMMIX models. Statistical differences in treatment × year least square means (LS-means) were tested by using the Tukey-Kramer multiple comparison method. Note that arithmetic means differ from the LS-means because of unequal sample sizes and patterns of missing data in addition to differences in models. The GLIMMIX procedure extends mixed models to generalized models that do not require normality of the underlying data distribution. LS-means from GLIMMIX are presented with their standard errors, unless indicated otherwise. Arithmetic averages and standard errors (within parentheses) are presented when describing raw inventory data because of issues related to subsampling, which tends to inflate sample size. These data are more easily compared to other studies.

Because seeded species and hence seed treatments differed for each site, all analyses are specific to each site. In addition to the problems of missing data, empty cells, and large numbers of zeros for some species, GLIMMIX had convergence problems for many of the responses.

RESULTS

Mechanical Treatments

Malpai Site

The cover of perennial grasses initially was less in the mechanically treated plots than in the control plots on the Malpai site (fig. 7A). Perennial grass cover in the crush + seed plots differed significantly from the control plots in 2001 ($p < 0.001$). The LS-mean for plains bristlegrass canopy cover in 2001 was 13.5 (1.3) percent in the crush + seed plots while the average cover of this grass on the control and crush plots was less than 1 percent ($p < 0.001$). Plains bristlegrass was the only seeded perennial grass species to show increased cover post-treatment, but this increase was lost after the dry year in 2003, and the species responded like the other perennial grass species afterwards.

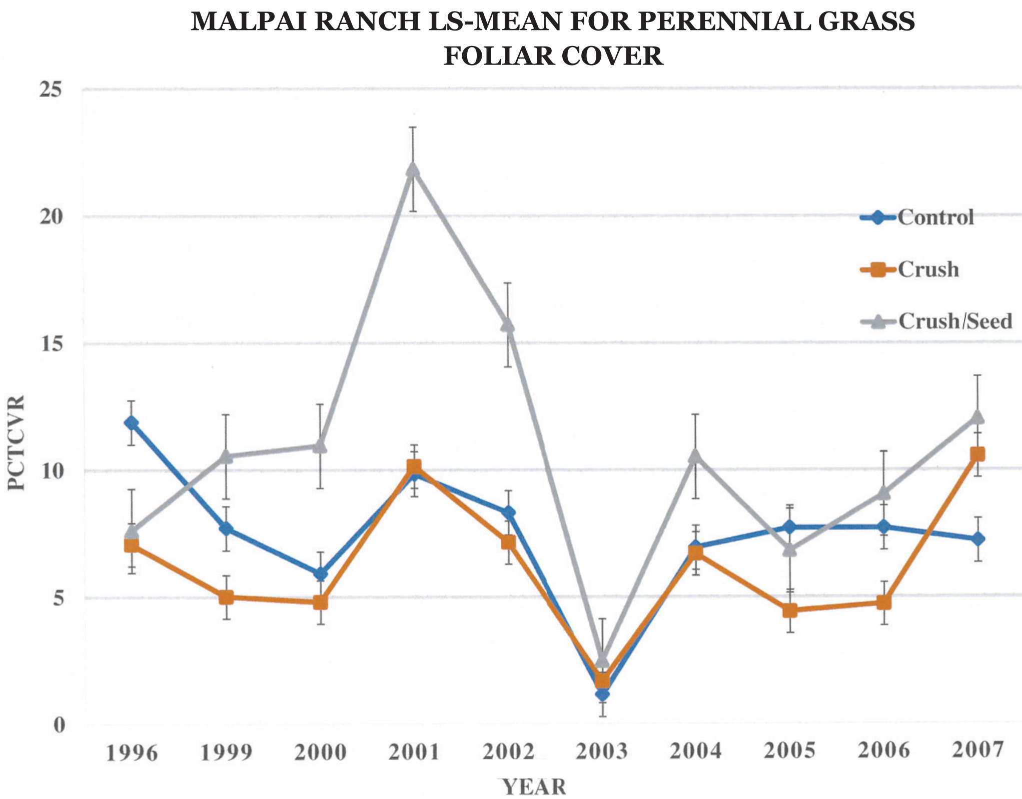
Of all the analyses conducted on data from the Malpai site, only the woody species category indicated a significant decline ($p = 0.002$) caused by the treatments (fig. 7B). The woody species cover on the two treatment plots prior to crushing or crushing + seeding (fig. 7B) was not significantly different from the control plots. The cover of woody species declined immediately after crushing and crushing + seeding and remained less than the control plots for the entire study period. Woody species were primarily mesquite, whitethorn, and tarwort, which occurred on all plots, but could include creosote bush (*Larrea tridentata*), catclaw mimosa, broom snakeweed, soapweed yucca, and pricklypear (*Opuntia* spp.). The differences between the two mechanical treatments were not statistically significant in any year.

Yearly fluctuations in cover were significant for 25 species or physical attributes on the Malpai site. Measurements indicated that seven species, including all woody species, had a significant treatment × year interaction.

Whitethorn cover declined after crushing + seeding and remained lower until 2003, when it began increasing. Mesquite and tarwort also declined after the two mechanical treatments in 1996, and their cover remained low throughout the period until 2007.

The bare soil and rock category fluctuated throughout the study, usually following the precipitation fluctuations, but the differences among treatments and controls were not

(A)



(B)

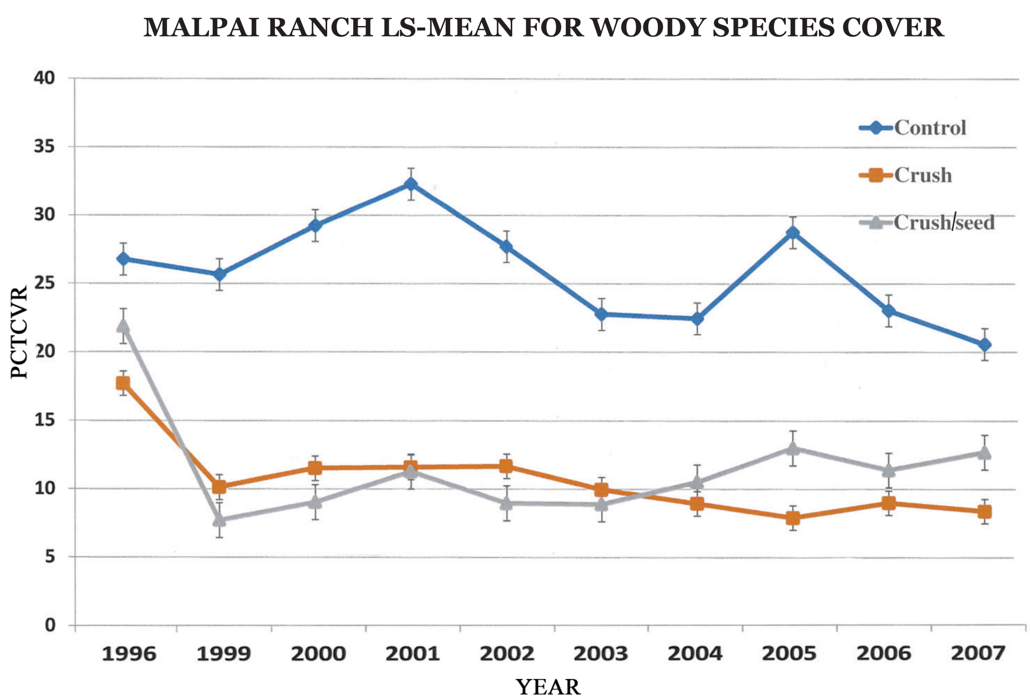


Figure 7—Fluctuations in mean foliar cover for perennial grasses (A) and for woody species canopies (B) related to treatment and weather effects at the Malpai Ranch site from 1996 through 2007.

significant. The differences among years were significant for all treatments. The average bare ground cover among all treatments in 2003 was between 65 and 73 percent, whereas in 2006, the bare ground cover was between 24 and 35 percent, depending on treatment.

Grass production and total annual production were significantly higher in the crush + seed plots than in the control or crush plots, which were similar (table 1). The yearly differences between the crush + seed plots and the control and crush plots were significant for grass production ($p = 0.00002$ and $p < 0.001$, respectively) and for total annual production ($p < 0.001$). Perennial grass production was over 90 percent of the total annual production for the crush + seed plots in 2000, but this contribution was reduced to 73 percent in 2007.

Table 1—Average perennial grass production and average total annual herbaceous plant production in pounds per acre with standard errors in parentheses, by year, Malpai Ranch site, southeastern Arizona.

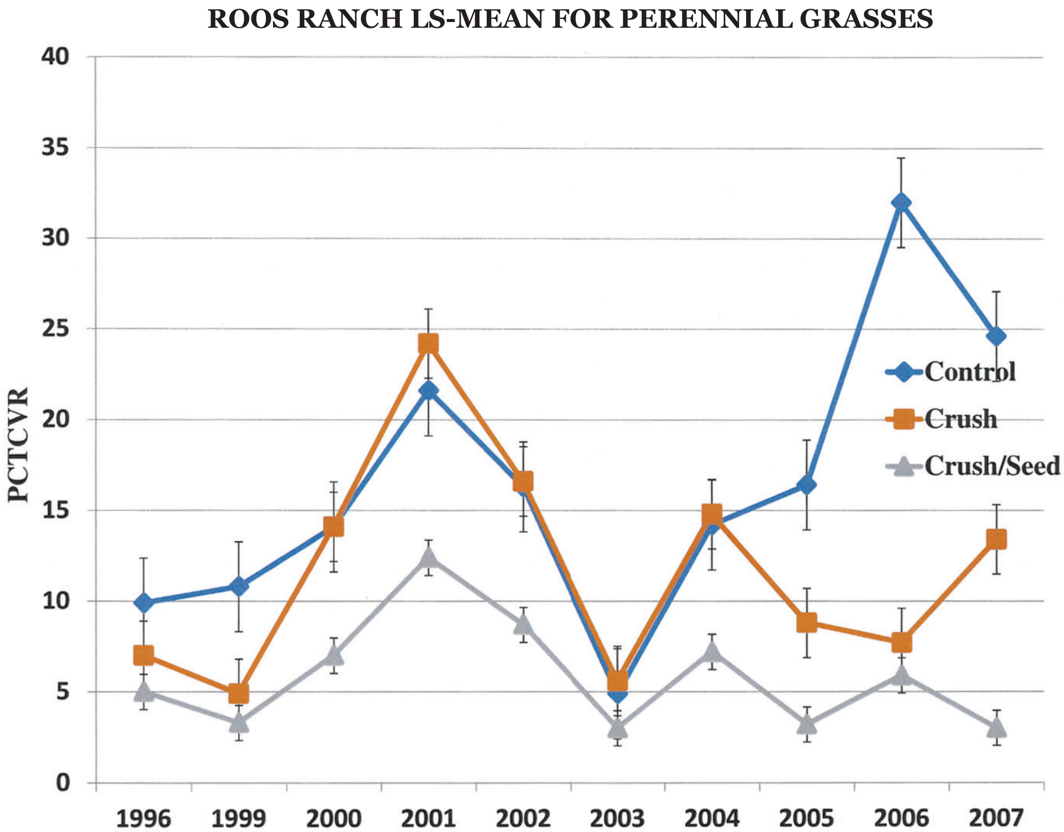
		Treatment year							
Treatment		**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**
Control									
	Perennial grass	146 (108)	132 (97)	426 (184)	118 (51)	113 (51)	150 (95)	52 (8)	172 (88)
	Total annual production	201 (142)	238 (149)	569 (200)	249 (94)	190 (66)	382 (208)	306 (18)	290 (124)
	Perennial grass (%)	73	56	75	47	60	39	17	59
Crush									
	Perennial grass	197 (100)	237 (64)	300 (62)	81 (18)	338 (131)	38 (27)	126 (39)	226 (17)
	Total annual production	345 (132)	655 (159)	542 (61)	224 (31)	488 (150)	311 (46)	334 (30)	506 (81)
	Perennial grass (%)	57	36	55	36	69	12	38	45
Crush + Seed									
	Perennial grass	507 (179)	439 (121)	1,049 (286)	296 (75)	373 (127)	386 (234)	64 (25)	460 (193)
	Total annual production	560 (155)	784 (278)	1,269 (315)	628 (175)	538 (159)	680 (264)	302 (11)	632 (187)
	Perennial grass (%)	90	56	83	47	69	57	21	73

Roos Site

Only two species, bush muhly ($p < 0.002$) and three-awn grass ($p < 0.003$), showed a significant treatment effect on the Roos site. Differences by year were significant for 26 species or physical attributes. Significant treatment × year interactions were identified for eight categories, including perennial grass cover and woody species cover ($p < 0.001$ to $p = 0.007$). The perennial grass foliar cover for all three treatments was similar in 1996 and all three fluctuated, with peaks in 2001 and 2004 and a decline in 2003 (fig. 8A). The important nonnative species Lehmann lovegrass increased significantly ($p = 0.007$) at the Roos site according to the analysis of treatment × year interactions. The average percent foliar cover of Lehmann lovegrass on the control plots ranged from 1.6 (1.0) percent to 11.1 (7.4) percent for all plots in 2006.

The cover of woody plants, primarily mesquite, initially was similar for all treatments (fig. 8B). The woody species cover on the treated plots declined after treatment and fluctuated significantly ($p < 0.001$) throughout the period. There were significant interactions for foliar cover on eight groups. The percentage of the soil surface not covered by plants was similar regardless of treatment.

(A)



(B)

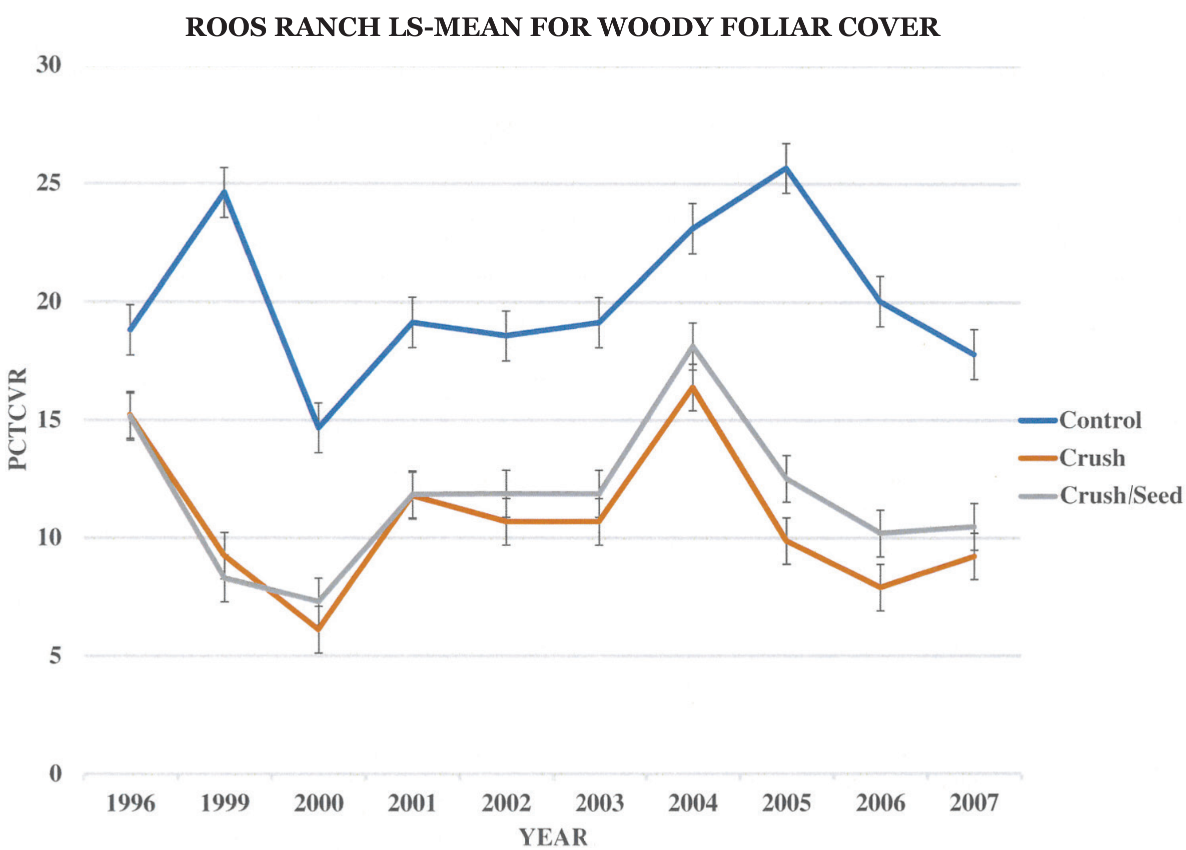


Figure 8—Fluctuations in mean foliar cover for perennial grasses (A) and for woody species canopies (B) related to treatment and weather effects at the Roos Ranch site from 1996 through 2007.

Total annual perennial grass production and total annual production in dry pounds per acre were estimated (table 2). The analysis for all perennial grass species ($P < 0.001$) and for total annual production ($p < 0.001$) on the Roos site indicated significant differences among years but not among treatments or treatment × year interactions.

Table 2—Average perennial grass production and average total annual herbaceous plant production in pounds per acre with standard errors in parentheses, by year, at the Roos Ranch site, southwsestern New Mexico.

		Year				
Treatment		**2000**	**2001**	**2002**	**2003**	**2004**
Control						
	Perennial grass	222 (49)	524 (162)	685 (286)	338 (147)	488 (187)
	Total annual production	571 (107)	1,004 (78)	941 (246)	624 (159)	665 (215)
	Perennial grass (%)	39	52	73	54	73
Crush						
	Perennial grass	485 (161)	1,150 (453)	1,068 (390)	460 (170)	629 (272)
	Total annual production	943 (283)	1,535 (425)	1,376 (386)	927 (236)	866 (306)
	Perennial grass (%)	51	75	78	50	73
Crush + Seed						
	Perennial grass	468 (344)	850 (569)	673 (71)	318 (33)	512 (47)
	Total annual production	774 (349)	1,768 (617)	1,178 (617)	738 (81)	689 (76)
	Perennial grass (%)	60	48	57	43	74

The analysis of year × treatment effects indicated that the cover of bare ground was similar throughout the study. Ten of the 12 plots had the greatest amount of bare ground cover in 2003, with an average of 63.8 (5.4) percent and the least bare ground in 2006 with an average of 17.6 percent. All 12 plots had low observed amounts of bare ground that year.

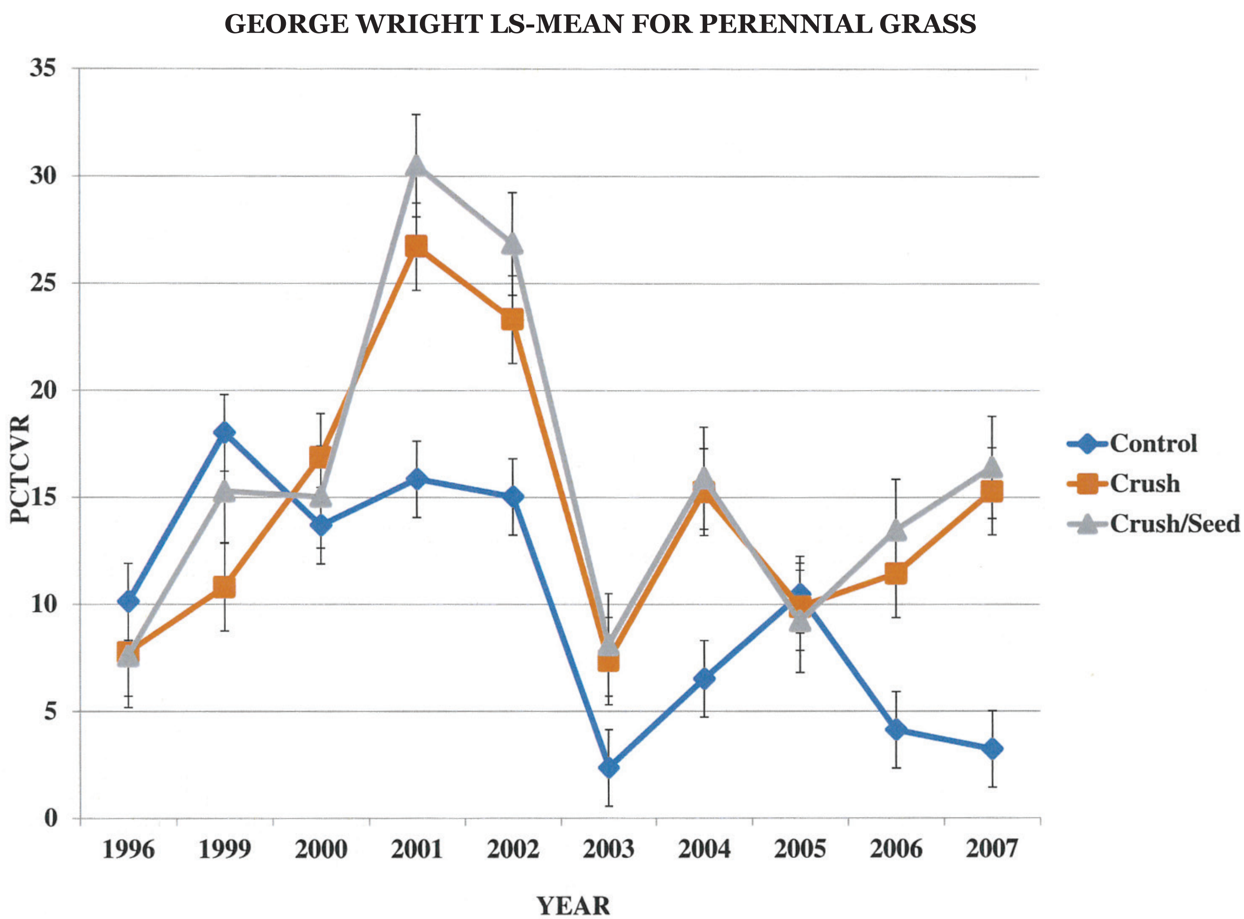
George Wright Site

No significant treatment effects were identified at the George Wright site. However, 26 species or physical attributes had significant yearly differences and 8 had significant treatment × year interactions ($p < 0.001$ to $p < 0.004$). Plains bristlegrass, similar to measurements at the Malpai site, was the only seeded species to show a positive impact of treatments, but the increases of 2001 and 2002 were lost in 2003. Increases were observed in both the crush and crush + seed plots. Perennial grass cover in the treated plots and in the control plots declined sharply in the dry year of 2003. Cover of perennial grasses increased in the treated plots after 2005 and declined in the control plots (fig. 9A).

The average cover of woody species was not significantly different among plots in 1996 before treatments; however, it declined in 1999 on the mechanically treated plots while woody cover on the control plots remained unchanged (fig. 9B). The crush and crush + seed treatment plots were similar throughout the remaining period.

The bare soil category within the three treatments increased and decreased throughout the period and generally followed the same pattern across treatments. Litter cover was relatively stable but increased in all categories in 2003.

(A)



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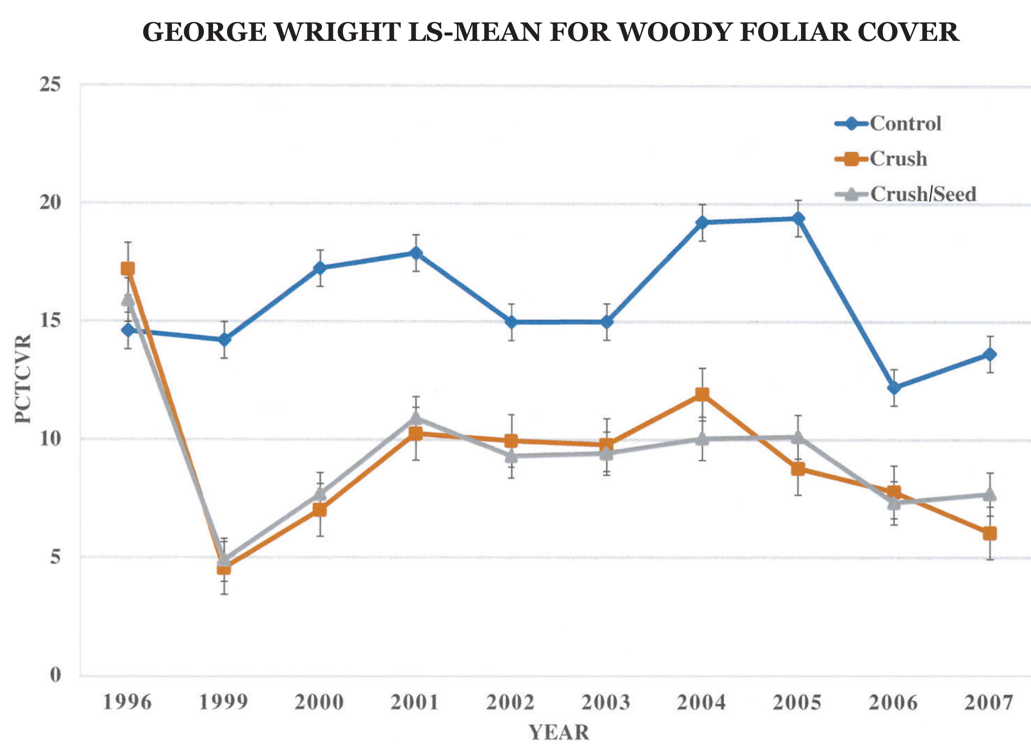


Figure 9—Fluctuations in mean foliar cover for perennial grasses (A) and for woody species canopies (B) related to treatment and weather effects at the George Wright pasture site from 1996 through 2007.

Perennial grass production and total annual production showed significant yearly ($p < 0.001$) and treatment differences between the control plots and the crush plots in 2001, 2002, and 2003 (table 3). The controls and the crush + seed plots were similar to each other during the study period. The control plots had a significantly lower total annual production ($p = 0.002$) in 2000 (530 (98) pounds per acre) than the crush plots (1,244 (289) pounds per acre), but the controls and the crush + seed plots (853 (254) pounds per acre) were not significantly different.

Table 3—Average perennial grass production and average total annual herbaceous plant production in pounds per acre with standard errors in parentheses, by year, George Wright pasture site, southwestern New Mexico.

		Year							
Treatment		**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**
Control									
	Perennial grass	454 (87)	246 (56)	251 (48)	71 (13)	98 (12)	115 (50)	78 (29)	97 (50)
	Total annual production	530 (98)	397 (73)	335 (48)	115 (18)	170 (15)	191 (62)	237 (41)	217 (60)
	Perennial grass (%)	86	62	75	62	58	60	33	45
Crush									
	Perennial grass	1,112 (296)	674 (120)	830 (108)	225 (28)	330 (95)	194 (52)	176 (40)	269 (41)
	Total annual production	1,244 (289)	866 (90)	982 (146)	318 (45)	451 (108)	369 (36)	310 (34)	626 (281)
	Perennial grass (%)	89	78	84	71	73	52	57	43
Crush + Seed									
	Perennial grass	716 (182)	610 (184)	737 (253)	204 (82)	210 (52)	195 (100)	190 (47)	464 (103)
	Total annual production	853 (254)	854 (223)	774 (222)	261 (83)	345 (96)	369 (81)	347 (75)	578 (120)
	Perennial grass (%)	84	71	95	78	61	53	55	80

Prescribed Burning Treatments

Malpai Site

The eight mechanically treated plots at the Malpai site were burned in the afternoon of June 20 and in the morning of June 21, 2005. Weather conditions in the middle of the afternoon burning period were: air temperature 100 °F, relative humidity 16 percent, and variable winds.

The postfire survey checked the 64 previously marked plants in the burned plots, which represented all three species of interest (mesquite, whitethorn, and tarwort), for fire damage to the crowns and trunks and stems. The 32 trees and shrubs in the control plots were also measured. Forty-seven percent of the marked plants had not been impacted by fire and 30 percent had more than 75 percent of the crown consumed. Eleven percent had minor damage to the crown, and the remaining plants (12 percent) had damage to between 25 and 74 percent of their crowns. Posttreatment observations indicate that this area showed the least amount of sprouting of burned brush relative to the other two ranch sites. Some areas with larger trees and greater fuel accumulations burned very hot.

Prior to the prescribed burn, the three species in the combined crush and crush + seed plots had an average crown area of 17.6 (3.1) square feet (table 4) and an average height of 2.9 (0.2) feet (table 5).

Table 4—Average crown area in square feet with standard errors in parentheses for trees before the prescribed burning treatment in 2005 and 3 years later, by research site.

Treatment and trees measured	Average crown cover, Malpai Ranch site	Average crown cover, Roos Ranch site	Average crown cover, George Wright pasture site
All trees in treated plots, 2005	17.6 (3.1)[a]	51.2 (9.8)	31.6 (6.2)
All trees in treated plots, 2008	26.2 (3.2)	32.5 (4.8)	34.3 (4.9)
Preburn burned trees, 2005	21.2 (5.4) (n = 34)	63.0 (15.0) (n = 39)	37.0 (12.9) (n = 27)
Burned trees, 2008	21.6 (4.2)	31.5 (6.9)	37.1 (7.0)
Unburned trees, 2005	13.4 (2.2) (n = 30)	32.8 (7.5) (n = 25)	27.7 (5.4) (n = 37)
Unburned trees 2008	31.4 (4.8)	34.0 (6.0)	33.0 (6.7)
Control 2005 (n = 32)	20.8 (2.6)	90.9 (23.0)	82.8 (31.5)
Control 2008	25.3 (2.8)	100.7 (27.8)	83.6 (29.7)

[a] Trees in the Malpai site were 35 percent mesquite, 53 percent whitethorn, and 12 percent American tarwort.

Table 5—Average height in feet with standard errors in parentheses for trees before the prescribed burning treatment in 2005 and 3 years later, by research site.

Treatment and trees measured	Average tree height, Malpai Ranch site	Average tree height, Roos Ranch site	Average tree height, George Wright pasture site
All trees in treated plots, 2005	2.9 (0.2)[a]	2.6 (0.2)	2.2 (1.1)
All trees in treated plots, 2008	3.6 (0.2)	2.7 (0.2)	2.5 (0.1)
Preburn burned trees, 2005	3.2 (0.3)	2.8 (0.3)	2.5 (0.3)
Burned trees, 2008	3.2 (0.3)	2.6 (0.3)	2.7 (0.2)
Unburned trees, 2005	2.7 (0.2)	2.2 (0.2)	2.0 (0.2)
Unburned trees, 2008	4.1 (0.3)	2.9 (0.2)	2.3 (0.2)
Control, 2005	3.4 (0.2)	3.4 (0.3)	2.6 (0.3)
Control, 2008	3.5 (0.2)	3.7 (0.3)	2.8 (0.2)

a Trees in the Malpai site were 35 percent mesquite, 53 percent whitethorn, and 12 percent American tarwort.

None of the treatments or the treatment × year interactions was significant. In 2005, before the burning, average crown areas were similar among the control plots and the treatment plots (table 4). Crown areas, such as that of mesquite (fig. 10), and tree heights in 2008 were significantly different from those in 2005. The burning treatments produced significant declines in these attributes for most treatments in 2006, but most plants recovered by 2008. Only one tarwort did not resprout. The control plot plants had increases in crown areas, but the changes in height were small.

The analysis of tree height of mesquite indicated significant differences between 2005 and 2008, including an increase for crush + unburned trees between 2005 and 2006 and for crush + seed + unburned trees between 2006 and 2008. Heights of the crush + burned trees declined after the fire and did not recover to their average pretreatment height by 2008.

There were no significant changes in crown area or height for tarwort caused by the prescribed fire. The analysis for whitethorn, however, indicated that crown area of burned trees in 2008 was larger than in 2006. The average crown area for the treated plots declined from 22.5 (5.4) to 16.0 (3.0) square feet after the burns but increased to 28.7 (4.5) square feet in 2008. The differences in height of whitethorn were not significant.

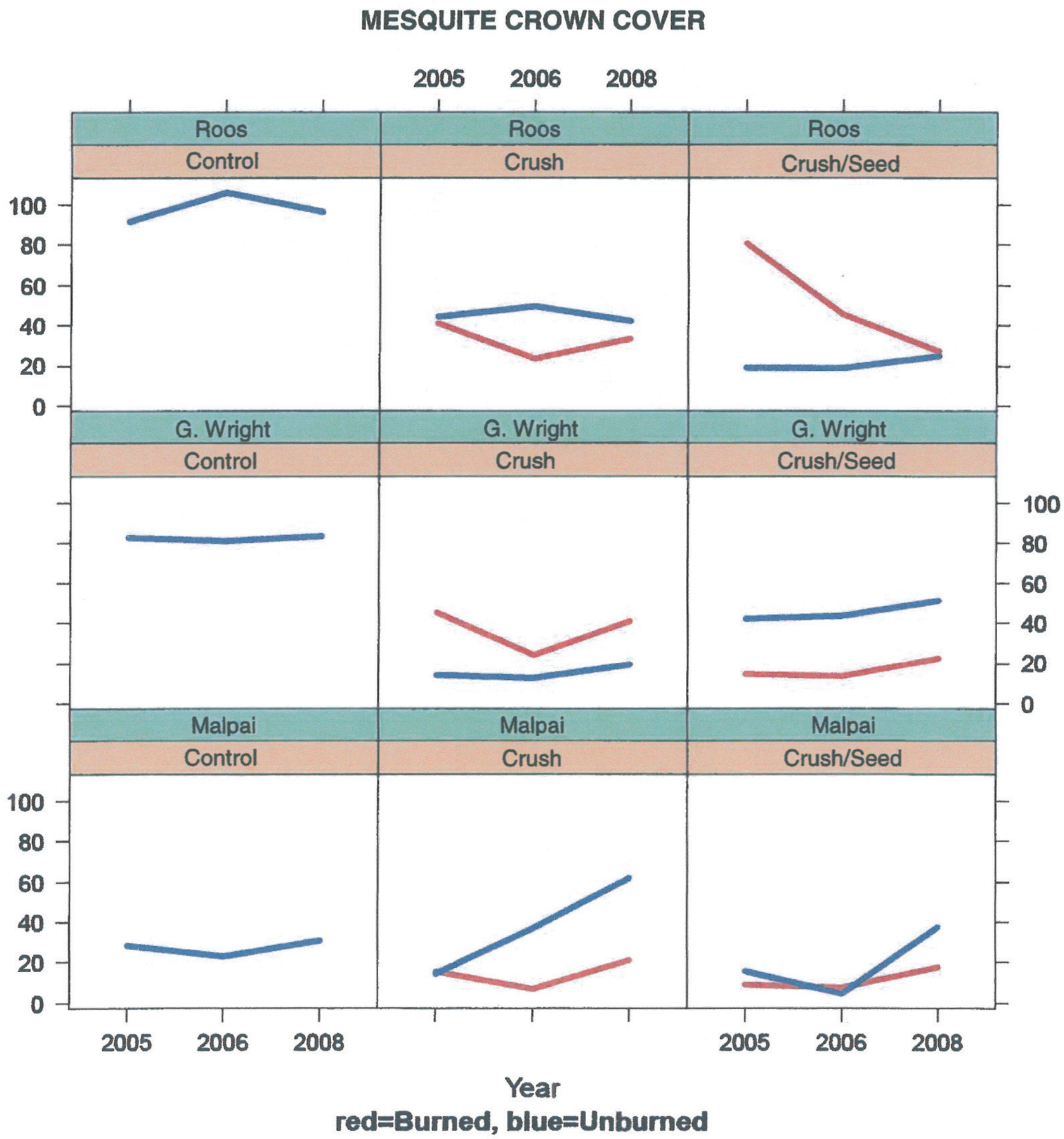


Figure 10—Fluctuations in average crown cover (square feet) from 2005 through 2008 in the burned plot and the control plots for all three research sites. The blue line indicates changes in unburned trees within treatment plots.

Roos Site

The eight treated plots at the Roos site were burned on the morning of June 8, 2005 (fig. 11). Weather conditions in the middle of the burning period were: air temperature 90 °F, relative humidity 28 percent, and winds 12 to 14 miles per hour from the south.

The postfire survey evaluated the 64 marked plants for fire damage to the mesquite crowns and woody trunks and stems. Thirty-nine percent of the trees had not been impacted by fire and 38 percent had more than 75 percent of the crown consumed. Eleven percent had minor damage to the crown, and the remaining plants (12 percent) had damage to between 25 and 74 percent of their crowns. With one exception, all burned brush plants sprouted after treatment.

Prior to the prescribed burn, the average mesquite in the crush and crush + seed plots had a crown area of 51.2 (9.8) square feet and a height of 2.6 (0.2) feet. Trees that were burned had an

Figure 11—The Douglas Ranger District fire crew conducting the prescribed burn of mesquite at the Roos Ranch site (photo by Gerald J. Gottfried, USDA Forest Service).

initial average crown area of 63.0 (15.0) square feet and an average height of 2.8 (0.3) feet while unburned trees in the treated plots averaged 32.8 (7.5) square feet in crown area and had an average height of 2.2 (0.2) feet (tables 4, 5). This apparent difference in the size of burned trees could indicate a heavier fuel load surrounding larger trees or a preference by the fire crew to ignite larger trees. In 2008, the burned trees had an average crown area of 31.5 (6.9) square feet and an average height of 2.6 (0.3) feet.

The analyses indicated that there were no significant differences for treatment or treatment × year interactions for both crown area and total height. The only significant differences were between 2008 and 2005 and between 2008 and 2006 (fig. 10). Average height data for the burned and unburned mesquite trees on the plots treated with prescribed fire and on the control plots show a large increase for crush + unburned trees between 2005 and 2006. The crush + seed + unburned trees also indicated an increase in height between 2006 and 2008 (table 5). Heights and crown cover (table 4) of the crush + burn trees declined after the fire and did not recover to their average pretreatment levels by 2008.

George Wright Site

The eight treated plots at the George Wright site were burned in the afternoon of June 8, 2005. The temperature was 97 °F and the humidity was 12 percent when ignitions began. At the conclusion of the operation winds were 4 to 6 miles per hour from the southwest.

The postfire survey evaluated the 64 marked mesquite trees for fire damage to the crowns and woody trunks and stems. Fifty-eight percent of the brush had not been impacted by fire and 22 percent had more than 75 percent of the crown consumed. Twelve percent had minor damage to the crown, and the remaining plants (8 percent) had damage to between 25 and 74 percent of their crowns. Most burned shrubs sprouted.

Prior to the prescribed burn but after mechanical treatments, the average mesquite in the crush and crush + seed plots had a crown area of 31.6 (6.2) square feet and a height of 2.2 (0.1) feet. The mesquite in the control plots had an average crown area of 82.8 (31.5) square feet and an average height of 2.6 (0.3) feet (tables 4, 5). The trees on the control plots did not appear to have grown as much in crown area as the control trees at the Malpai and Roos sites.

Unlike the results from the Malpai and Roos sites, there were no significant differences in crown area among the years for the four active treatment options (fig. 10) although there were fluctuations in this attribute. In 2005, before the burning, crown areas appeared similar among the control and the crush + seed + unburned and crush + burned trees. The crush + unburned and crush + seed + burned trees were similar but had smaller crowns. The data for 2006 indicate significant declines for all categories except for the controls and the crush + seed + unburned. The crown area of all four treatments recovered or increased between 2006 and 2008.

The analysis of tree height did indicate significant differences for mesquite by year. Trees in 2006 were smaller than in 2005 or 2008. There was a relatively large decrease for the crush + burned and crush + seed + burned trees following the fire, but these trees grew rapidly between 2006 and 2008. The control, crush + unburned, and crush + seed + unburned trees showed little change between 2005 and 2006, and all indicated increases between 2006 and 2008.

SUMMARY AND DISCUSSION

Mesquite has expanded over the past 150 years from more sheltered and mesic grassland drainages and riparian zones into open grasslands, where it often becomes the dominant species (Wilson et al. 2001). There have been numerous attempts, using different techniques, to remove or reduce mesquite densities on the rangelands of Arizona and New Mexico, but no single strategy has yet been found effective at slowing or reversing mesquite encroachment into desert grasslands (Wilson et al. 2001). However, land managers continue to treat the mesquite cover on semidesert and desert grasslands in the Southwest to restore sustainability, ecological function, species diversity, and production of the grassland ecosystems. Martin and Morton (1993) report that perennial grass production more than doubled after mesquite was killed on one site.

The Forest Service's Rocky Mountain Research Station, the USDA Natural Resources Conservation Service, and their private and public cooperators established a study at three privately owned rangeland sites in southeastern Arizona and southwestern New Mexico to test the hypothesis that treatments that crushed the trees and shrubs with and without seeding native perennial grass species would increase the cover and productivity of native herbaceous species. Both types of treatments included prescribed fires to further reduce tree and shrub recovery. The combined treatments were not expected to kill the mesquite and other woody species but to reduce their dominance on the rangeland.

The study did not demonstrate significant differences in grass foliar cover and productivity between mechanical treatments with and without seeding native perennial grass species and applying prescribed burning. The cover of woody species, mainly mesquite, did significantly decline in some years. The report provides useful information about how perennial grasses and herbaceous vegetation reacted over a 10-year period to a long-term drought.

A summary of the study could be helpful. The research sites on three range sites were treated separately because of inherent differences, particularly differences in pretreatment vegetation, elevation, soils, and seeded perennial grass species. The efforts can be considered as three case studies. Treatment results for each site were analyzed separately for treatment, year, and treatment × year interactions. The analyses were based on measurements of changes in percent plant foliar cover or physical attributes, such as soil surface conditions, over the study period from 1996 through 2007, and to changes in the production of perennial grasses relative to total annual production from 2000 through 2007. Precipitation and other meteorological data were measured at weather stations at each site throughout the study, and species identified on the four study sites are listed in the Appendix.

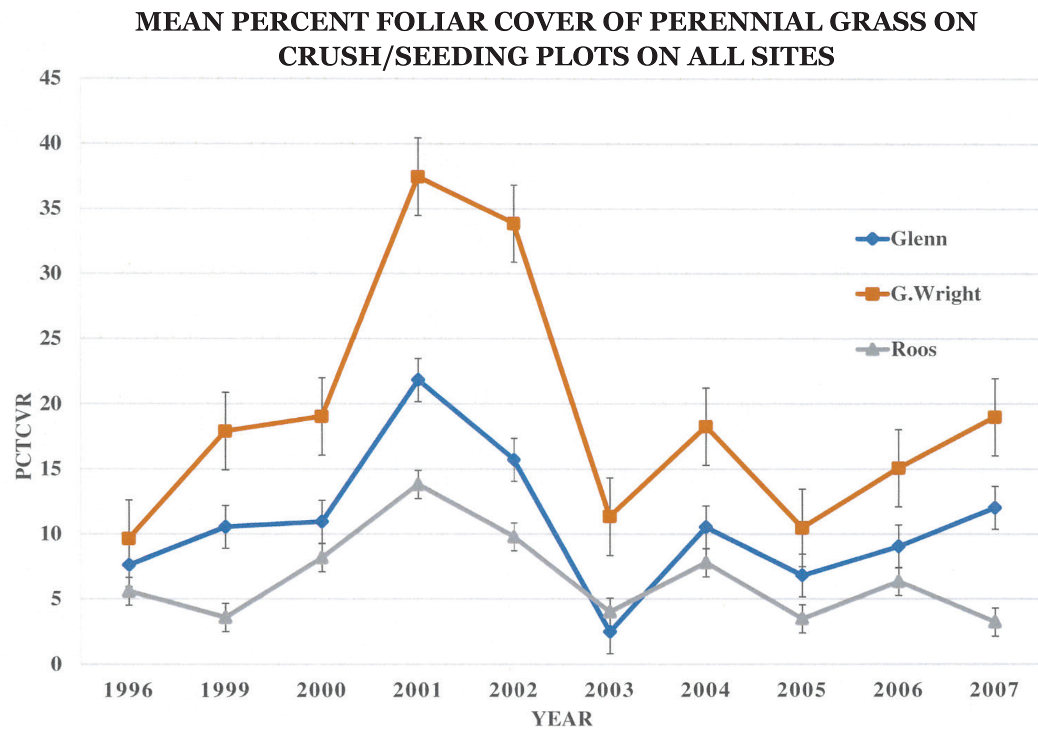
Changes in vegetation cover and herbaceous production were strongly influenced by the severe or extreme regional drought that began in 1999 and 2000. The Southwest was in drought for much of the study period and yearly fluctuations in vegetation or physical cover can be partially related to precipitation. For example, the increase in litter cover in 2003 within all three treatments at the George Wright site could be attributed to plants that died or were injured during the 2003 drought.

Vegetation success is largely influenced by the pattern of summer precipitation (Roundy and Beidenbender 1995). Many grass species put on 90 percent of their growth during this period (McClaran 1995). The relatively large number of significant year × treatment interactions indicates the influence that precipitation in the regional drought has on grass survival. The data collected after the 2003 drought basically describe how the plant stands were attempting to recover. For example, much of the significant changes in woody species cover, primarily mesquite, at the Roos site between 2000 and 2007 could probably be explained by fluctuations in precipitation. The warm-season precipitation in 2006 was 12.69 inches, the second highest value recorded at the Roos weather station during the study, and may account for some of the increase in woody species cover. Similarly, the low amounts of bare ground on all plots on the Roos site in 2006 probably reflect an increase in the cover of perennial grasses. Despite increases in cover or production after 2003, however, plant stands rarely achieved the pre-2003 densities or production levels. Although there were some differences at times and on some sites, the crush + seed treatment produced similar results to the crush treatment.

Analyses of the effects of prescribed burning showed initial declines in shrub crown area and height in 2005 on all areas, but most recovered to pretreatment levels by 2008. At the Malpai and Roos sites, the crown area and height measurements for mesquite were significantly different in 2008 relative to 2005. It appears that the burned trees and shrubs recovered from the burn damage in the 3 postburn years. At the George Wright site, only tree height was affected by the prescribed fire; height declined between 2005 and 2006 but recovered afterwards. The reason for the decline in crown cover of unburned trees in the crush plots at the George Wright site is unknown. Mesquite's ability to sprout, especially from buds on its roots, makes it difficult to kill. The burning treatment killed very few of the plants, although between 22 and 38 percent of the marked woody plants on the sites suffered at least 75 percent crown damage. Observations on repeatedly burned pastures in southern Arizona indicate that mesquite, while present, can be reduced to a low stature that renders it less of a competitor with grasses.

Although no attempt was made to compare the treatment effects on the three mechanically treated sites statistically, it is of interest to see how they compared. Though the graphs of the impacts of the crush + seed treatments on perennial grass foliar cover and woody grass foliar cover may appear similar across sites (fig. 12), the main statistical comparisons are relative to the control plots, as presented in the *Mechanical Treatments* section.

(A)



(B)

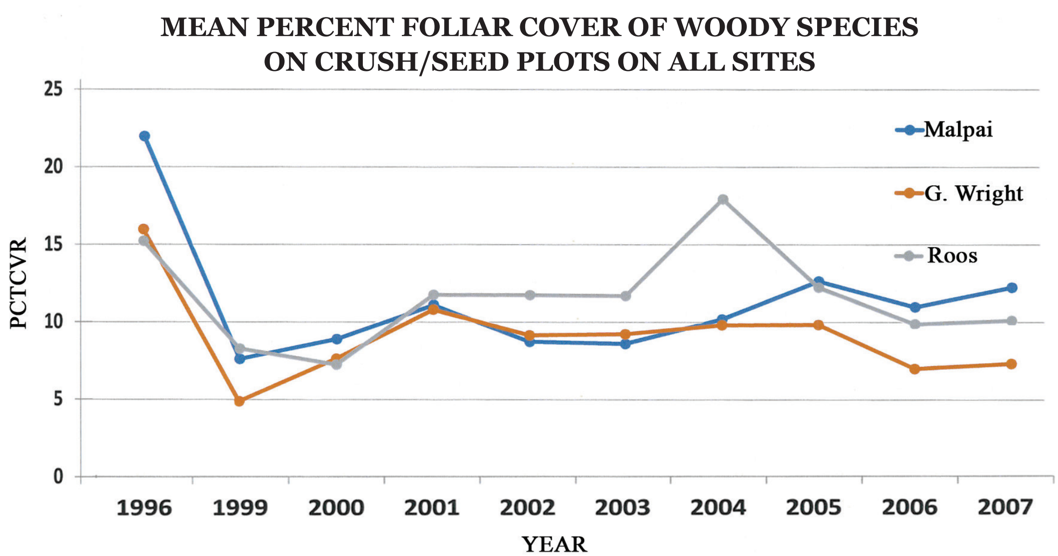


Figure 12—Observed comparison of changes in foliar cover for perennial grass canopies (A) and for woody species canopies (B) related to the crush + seed treatment on the research sites, by year. The three sites cannot be compared statistically.

Although the main hypothesis was not proven, the study raises several questions. Was the seeding of native perennial grass species worthwhile? Of all the species seeded, only plains bristlegrass became established. Is it worthwhile using these seed mixes in areas that are subjected to periodic drought conditions and where droughts may become more common in the future? Would the treatments have been more successful in achieving satisfactory covers of perennial native grasses if the regional drought had not occurred? Increased cover of grass was noted soon after the treatments and before 2003. Should managers anticipate a drier and warmer environment? Most projections are that the Southwestern Borderlands will become drier and hotter as the climate changes in the future (Archer and Predick 2008; Seager et al. 2007). A warmer climate even without a change in precipitation could affect the density and viability of less drought-tolerant species of plants and animals, causing them to decline or disappear from the landscape (Gottfried et al. 2012). Mesquite could increase in importance and possibly replace oak (*Quercus* spp.) on some of its lower elevation sites.

Would the recent mechanical crushing or crush + seed treatments been more successful with a different mix of native perennial grass species? Managers should consider this possibility when planning range restoration treatments. It is possible that a different mix of grass species, more adapted to drought, would have been more successful. Yet some have questioned whether a potentially successful seed mix even exists for semidesert grasslands (L. Allen, Malpai Borderlands Group, personal correspondence, 2016). The Natural Resources Conservation Service and university agricultural experiment stations are testing alternative species or varieties of native species that could be successful in a changing environment. A future test could reevaluate this hypothesis. If the experiment had been conducted in a moister period, and the cover and production of perennial grasses had increased, would the test be valid if the climate does become drier?

CONCLUSIONS

Restoration of deteriorated rangelands is a priority throughout the Southwest. Many of these rangelands now support relatively dense stands of woody species where open grasslands and savannas occurred historically. In the arid and semiarid regions, mesquite and its associate species are common dominants today. A variety of management techniques have been tried to eradicate or at least suppress the shrubs, but most have not been successful. The Forest Service's Rocky Mountain Research Station and its public and private collaborators attempted to restore semidesert grasslands in southeastern Arizona and southwestern New Mexico by crushing the woody tree and shrub cover and seeding native perennial grass species followed by burning the remaining shrubs as a site preparation tool. Some initial success was achieved in reducing the shrub cover and increasing the perennial grass cover and production, but the regional drought and differences between study implementation on different sites compromised the study and the increased grass cover could not be sustained. Plains bristlegrass was the only seeded grass to become established, and most native herbaceous species on the sites did not recover. The cover of seeded grasses was not sufficient to carry the prescribed fire into the remaining mesquites, and spot-burning was necessary.

Was the crushing treatment a failure? It is difficult to make this determination because of the drought. However, droughts historically have not been unusual in the region, and drier and warmer conditions are projected to increase in the future. The fact that the results were influenced by exceptionally dry conditions could have application in the future. It may be worthwhile to conduct another trial of this technique using a different mix of native, more drought-tolerant grass species seed. There is also interest in continuing the fire treatments to determine whether burning would eventually reduce woody plant cover and reduce competition with the grass stand.

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Appendix—List of all species identified on the four research sites.

Symbol	Scientific name	Common name, if available	--------Location where observed[a]--------			
ACCO	*Acacia constricta*	whitethorn	M			
ACOUR	*Acourtia* spp.	desert holly	M	R	G	S
AMBRO	*Ambrosia* spp.	ragweed	M	M		
ANDRO2	*Andropogon* spp.				G	
ARIST	*Aristida* spp.	three-awn grass	M	R	G	S
ASTER	*Aster* spp.	aster			G	
ATCA	*Atriplex canascens*	fourwing saltbush	M	R		S
BAABA	*Bahia absinthifolia*				G	
BAMU	*Baileya multiradiata*	baileya			G	
BASA2	*Baccharis sarothroides*	desertbroom			G	
BOBA	*Bothriochloa barbinodes*	cane bluestem	M	R	G	S
BOCH	*Bouteloua chondrosioides*	sprucetop grama	M			
BOCU	*Bouteloua curtipendula*	sideoats grama	M	R	G	S
BOER4	*Bouteloua eriopoda*	black grama	M	R	G	
BOGR2	*Bouteloua gracilis*	blue grama	M	R	G	
BOHI2	*Bouteloua hirsuta*	hairy grama	M	R	G	
BORE2	*Bouteloua repens*	slender grama	M			
BORO2	*Bouteloua rothrockii*	Rothrock's grama	M	R		
BRDE	*Brayulinea densa*				G	
BRICK	*Brickellia* sp.				G	
CABA	*Cassia bauhinioides*	locoweed		R		
CELAR	*Celtis reticulata*	netleaf hackberry				S
CHLI2	*Chilopsis linearis*	desert willow		R		
CODI	*Commelina dianthifolia*	dayflower		R		
CONDA	*Condalia* sp.	condalia, snakewood				S
CRCO	*Croton corybulosus*	croton	M	R	G	
CYLE8	*Cylindropuntia leptocaulis*	Christmas cactus		R		S
DAPU	*Dasyochloa pulchella*		M	R	G	
DECO	*Desmanthus cooleyi*			G		
DICA8	*Digitaria californica*	Arizona cottontop	M	R	G	S
ENNEA	*Enneapogon* spp.			R		
EPHED	*Ephedra* sp.	Mormon tea	M	R	G	
ERIN	*Eragnostis intermedia*	plains lovegrass		R	G	
ERLE	*Eragrostis lehmanniana*	Lehmann's lovegrass	M	R	G	
ERWR	*Eriogonum wrightii*	shrubby buckwheat			G	
EVOL	*Evolvulus* sp.				G	
FEROC	*Ferocactus* spp.	barrel cactus		R		
FLCE	*Flourensia cernua*	American tarwort, tarbush	M	R		S
GUSA2	*Gutierrezia sarothae*	broom snakeweed	M	R	G	S
HODE	*Hoffmansegia densa*	hog potato	M	R	G	
ISTE2	*Isocoma tenuisecta*	burroweed	M	R	G	S
KRLA	*Krameria lanceolata*				G	

(continued)

Appendix (continued)

Symbol	Scientific name	Common name, if available	--------Location where observed[a]--------			
LATR2	*Larrea tridentata*	creosote bush	M			
LEDU2	*Leptochloa dubia*	green sprangletop			G	
LOWR	*Lotus wrightii*	Wright's deervetch		R		
LYPH	*Lycurus pheloides*	common wolfstail		R		
MACH	*Magnolia champaca*				G	
MIAC3	*Mimosa aculeaticarpa* var. *biuncifera*	catclaw mimosa	M	R	G	S
MUAR2	*Muhlenbergia arenicola*	sand muhly			G	
MUPO2	*Muhlenbergia porteri*	bush muhly grass	M	R	G	S
MUTO2	*Muhlenbergia torreyi*	ring muhly			G	
OPPUNT	*Opuntia* sp.	pricklypear	M			S
OPSPI	*Opuntia spinosior*	cholla	M			S
PANSP	*Panicum hirticaule*	panic grass	M	R	G	
PAOB	*Panicum obtusum*	vine mesquite grass	M		G	S
PHASE	*Phaseolus* spp.	bean		R		
PHCU3	*Phyla cuneifolia*	P38		R	G	
PLMU3	*Pleuraphis mutica*	tobosagrass	M	R	G	S
POOB	*Polygala obscura*				G	
PRGL	*Prosopis glandulosa*	honey mesquite	M	R	G	S
RHMI3	*Rhus microphylla*	littleleaf sumac				S
RUMEX	*Rumex* sp.			R		
SCBR2	*Scleropogon brevifolius*	burrograss			G	
SEGR4	*Senegalia greggii*	catclaw acacia		R		
SEMA5	*Setaria macrostachya*	plains bristlegrass	M	R	G	S
SILE	*Sidia lepidota*				G	
SOEL	*Solarum elaeagnifolium*	horsenettle	M	R	G	S
SOHA	*Sorghum halepense*	Johnsongrass				S
SPAI	*Sporobolus airoides*	alkali sacaton			G	
SPCO	*Sporobolus contractus*	spike dropseed		R		
SPFL2	*Sporobolus flexuosus*	mesa dropseed		R	G	S
SPHAE	*Sphaeralcea* sp.	globemallow		R	G	
SPORO	*Sporobolus* sp.	dropseed	M	R	G	
SPWR2	*Sporobolus wrightii*	sacaton	M		G	S
TAAU	*Talinum aurantiacum*			R	G	
VEPO4	*Verbena* sp.				G	
YUEL	*Yucca elata*	soapweed yucca	M	R		
ZIGR	*Zinnia grandiflora*	desert zinnia		R		
ZINNI	*Zinnia* sp.	zinnia	M		G	
ZIOB	*Ziziphus obtusifolia*	crucifixion thorn				S
Sticky forb	[unidentified]				G	

[a] Research sites: M = Malpais Ranch; R = Roos Ranch; G = George Wright pasture; S = Sycamore Ranch

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