Structure and Function of Chihuahuan Desert Ecosystem
The Jornada Basin Long-Term Ecological Research Site
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Remediation Research in the Jornada Basin: Past and Future

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It seems as if the entire set of changes in the soil environment...ensures that mesquite will occupy those sites for long periods of time.

—Wright and Honea (1986)

Land degradation in most of the Chihuahuan Desert is characterized by a shift from grass- to shrub-dominated plant communities (Ballín Cortés 1987; Grover and Musick 1990; Fredrickson et al. 1998; see also chapter 10). This shift is associated with increased soil resource redistribution and spatial variability at the plant-interspace scale (Schlesinger et al. 1990; see also chapter 6). Earlier definitions focused more specifically on the loss of plant species, such as black grama (Bouteloua eriopoda), which were palatable to livestock (Nelson 1934). In 1958, it was estimated that one section (3.2 km^2) of black grama grassland could support 18 animal units yearlong, while a similar area dominated by mesquite (Prosopis glandulosa) dunes could support just three animal units (Jornada Experimental Range Staff 1958; see also chapter 13). It was recognized that overgrazing facilitated the increase of less palatable species, including shrubs. Consequently, the objectives of the first organized rangeland research in the Southwest were to identify proper techniques to restore grasslands that had been overgrazed (Jardine and Hurtt 1917; Havstad 1996). Today, we recognize the importance of multiple, interacting factors in addition to overgrazing, and research is more broadly focused on the recovery of ecosystem functions necessary to support multiple ecosystem services. This chapter details this extensive history of research to identify and develop technologies to revegetate, restore, reclaim, rehabilitate, or more generally remediate degraded rangelands.

The Society for Ecological Restoration considers that "an ecosystem has recovered when it contains sufficient biotic and abiotic resources to continue its development without assistance or subsidy. It will demonstrate resilience to normal ranges of environmental stress and disturbance. It will interact with contiguous ecosystems in terms of biotic and abiotic flows and cultural interactions" (Society for Ecological Restoration Science and Policy Working Group 2002). Although restoration of perennial grasslands is often cited as the ultimate objective of management intervention in the Southwest, we recognize that in many if not most cases complete restoration of a preexisting plant and animal community is impossible, even if we had perfect knowledge of all of the elements they contained. We also recognize that many of the historic management interventions discussed herein had more limited objectives. Revegetation is a primary objective where perennial plants have been completely lost from a site, whereas the term reclamation is used to refer to management designed to address a narrowly defined objective or set of objectives, such as erosion control. The word remediation is used throughout this chapter to include management designed to support revegetation, reclamation, and restoration objectives.

This chapter is organized into three sections. The first is designed to provide an overview of approaches developed and tested in the Jornada Basin and elsewhere in the region. The second places this work in the context of existing knowledge about ecological processes. The third section looks toward developing dynamic, ecologically based, landscape-level approaches that will benefit from increasing knowledge of long-term processes and patterns.

Historic Approaches

The history of remediation research in the Jornada Basin can be conveniently divided into three periods. The first began with the creation of the Jornada Experimental Range (JER) and emphasized improved livestock management. The second was associated with availability of inexpensive labor during the Great Depression of the 1930s, coinciding with the recognition that livestock management alone might be insufficient to reverse shrub encroachment into grassland. The third period was dominated by increased reliance on herbicides and mechanized shrub control.

Livestock Management (1912–1930s)

A number of state and federal experiment stations were established at the end of the nineteenth and beginning of the twentieth century. Research was designed to estimate the carrying capacity of rangelands during drought and nondrought years, to evaluate and demonstrate the use of water, mineral feeding stations, and fencing to control livestock distribution and increase the quantity and quality of meat production. A number of livestock exclosures were established, and in some cases, clipping trials were initiated to determine sustainable levels of plant utilization. On the JER, four large (640 acres each) exclosures were established during the 1930s: the natural revegetation, the mesquite sand hills artificial revegetation, the gravelly ridges (creosotebush *Larrea tridentata*) artificial revegetation exclosure, and the Doña Ana moisture conservation plots exclosure. Changes in vegetation composition inside the exclosures generally followed changes in the surrounding landscape, a pattern repeated in many areas in the Southwestern United States. While perennial grass cover fluctuated both inside and outside exclosures in response to rainfall variability, the general trend was increased shrub dominance. The natural revegetation exclosure was located on a mesquite–black grama ecotone. It is now completely covered by mesquite duneland. The plant communities in the other three exclosures were already shrub dominated when established (Buffington and Herbel 1965) and continue to be shrub dominated today.

Livestock management research continues today with the development of improved technologies to control livestock distribution through the use of GPS and GIS technologies. These technologies will allow site-specific management of relatively small areas in extensive rangeland systems without fencing (Anderson 2001; see also chapter 13).

Labor-Intensive and Mechanical Approaches (1930s)

Campbell (1929) suggested that in the absence of grazing, grasslands would eventually replace mesquite dunelands through natural succession. Although livestock exclusion continues to be discussed even today as a key to the restoration of Southwestern landscapes (Donahue 1999), the failure of livestock management alone to reverse shrub invasion was beginning to be recognized by the 1950s (JER Staff 1958). It is now clear that some degraded sites will not be remediated simply by exclusion of domestic livestock (Bestelmeyer et al. 2003a; see also chapter 10).

Much of the early experimentation in the Jornada Basin was completed by individuals employed through government programs designed to stimulate the economy by increasing employment. Despite the fact that few of them had formal scientific training, their experiments and other projects have generated extremely valuable data due to their long-term nature and because treatments were often replicated across the landscape. The Civilian Conservation Corps (CCC) provided a large supply of labor during the Depression years of the 1930s. There were approximately 50,000 CCC workers in New Mexico between 1933 and 1942 (Melzer 2000). There were three permanent camps and one temporary CCC camp located in the Jornada Basin.

The workers built roads, established many of the experiments listed in table 14-1, and developed a recreational facility at Ropes Springs on the eastern side of the basin.

Few detailed records of the manipulations completed by the CCC have been preserved, but many of the structures and patterns created can be detected both on the ground and in aerial photographs dating to 1935 (figure 14-1; Rango et al. 2002), and the objectives and results of some of the experiments are summarized in internal reports.

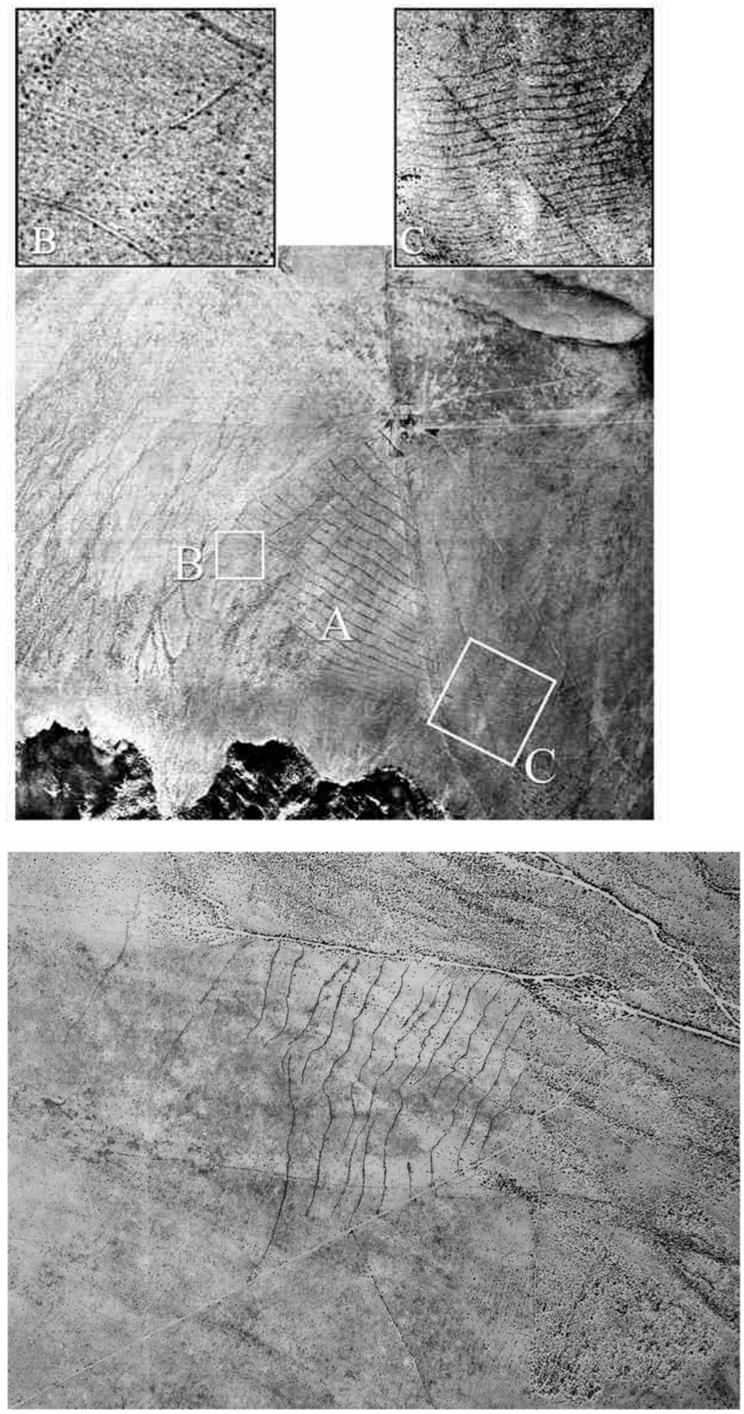
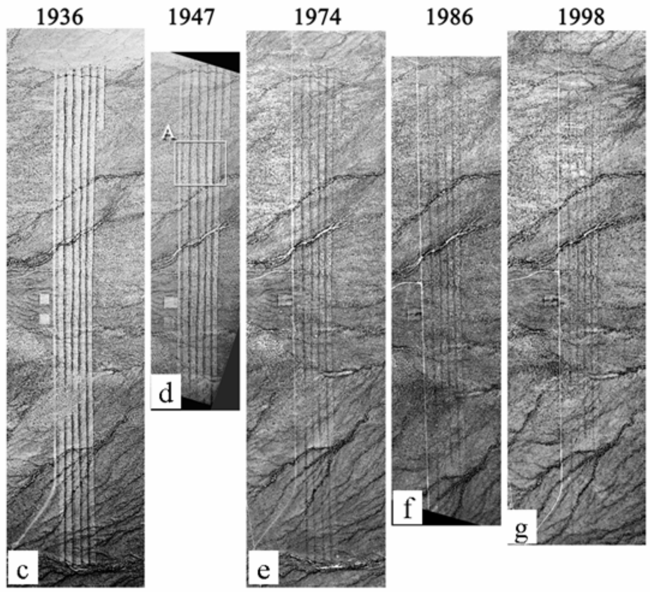
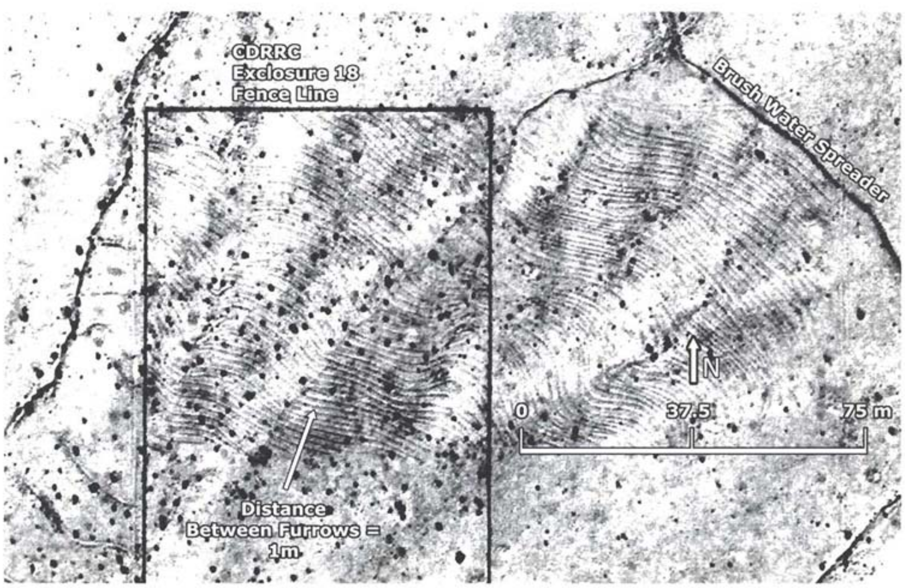


Fig. 14-1. Early remediation experiments visible in aerial photographs (from Rango et al. 2002; see Table 14-2).





Individuals hired with funding from the National Industrial Recovery Act in 1933 were responsible for much of the project planning, supervision, and documentation (Valentine 1942). Many of these individuals continued with careers in rangeland management after World War II

(Ares 1974). Economic Recovery Act funding was also used during this period for supervisory personnel.

There was a clear understanding in the 1930s that grass establishment in shrublands, especially mesquite dunelands, was probably limited by multiple factors, including soil instability (which leads to seed burial and root exposure), preferential grazing on grasses by native herbivores, and competition by existing plants. Various approaches were tried to enhance grass establishment. The treatments can be classified into five basic groups: seeding and transplanting, microsite manipulations, shrub removal, water redistribution, and small mammal control. Livestock were excluded from most of the experimental areas. In some cases, livestock exclusion was included as an experimental treatment. Although many of the manipulations appeared to increase grass establishment temporarily, few had significant lasting effects on plant community composition. Some of the treatments applied in the 1930s could no longer be detected in aerial photographs by 1968, whereas others were still visible in 1996 (table 14-2).

Table 14-1. Nonherbicide remediation trials in the Jornada Basin (USDA-ARS Jornada Experimental Range and NMSU College Ranch now the Chihuahuan Desert Rangeland Research Center). Original units and plant names from the reports are retained. For a summary of herbicide trial results, see text and Herbel and Gould (1995).

Treatment	Livestock Excluded?	Year(s)	Plant Community	Soil	Location (Pasture #)	Results	Source
Rodent exclusion + Mesquite brush piles + Denude dune tops (to facilitate wind erosion) + Trenches between dunes (to catch topsoil and seed) + Diesel oil applied to mesquite	Yes, in 1934	1934 (rodent exclude - 1936)	Mesquite dune	Onite (coarse-loamy, mixed Typic Haplargid)	Mesquite Sandhills Artificial Revegetation Exclosure (4)	Unsuccessful	JER Staff 1958; Valentine 1942
Rabbit and rodent control attempted throughout 640-acre exclosure and 1 mile buffer strip with poisoned grain in Jan., Feb. and Nov., 1934 for rodents and poisoned salt blocks for rabbits.	Yes, in 1934	1934		Onite (coarse-loamy, mixed Typic Haplargid)	Mesquite Sandhills Artificial Revegetation Exclosure (4)	Unsuccessful. No data on kill % encountered.	Valentine 1942
Livestock exclusion	Yes, in 1934	1934	Mesquite/ grassland transition	Onite (coarse-loamy, mixed Typic Haplargid)	Mesquite Sandhills Natural Revegetation Exclosure (4)	By 1955, area occupied by mesquite increased 89% and area occupied by black grama decreased 91%. By 1980, there was a net loss of 4.6 cm of soil and the entire 640 acres was covered by mesquite dunes.	JER Staff 1958; Valentine 1942; Gibbens et al. 1983
Trenching to 26 inches around dune interspaces + Transplanting grasses and Atriplex canescens	Yes, in 1934	1934-	Mesquite dune	Onite (coarse-loamy, mixed Typic Haplargid)	Mesquite Sandhills Artificial Revegetation Exclosure (4)	Unsuccessful	JER Staff 1958; Valentine 1942

Treatment	Livestock Excluded?	Year(s)	Plant Community	Soil	Location (Pasture #)	Results	Source
Contour terraces constructed with a road grader. Twenty-one terraces 8 feet wide x 16-20 inches high leaving 6-8 foot wide shallow pit on upslope side. Spacing 100-300= with closer spacing at top of slope. Added rock "weeps" to allow water to percolate through after several years to minimize breaks. Some terraces seeded to "various native and cultivated plants".	Yes (for at least 11 years)	1935	Black grama (upper slope), creosote (mid-slope) and Mormon tea/short-lived perennial grasses (footslope)	A Compact gravelly clay loam underlaid by a heavier compact clay loam and in places caliche at 24-36 inches. Higher permeability higher on slope.	210 acres on north-facing slope of Dona Ana Mountains	"Little improvement that can be attributed to the terraces has taken place over the area in general". Temporary snakeweed increase on upslope side of terraces. Black grama increased in the one inter-terrace quadrat in which it occurred, but was less vigorous than in other areas. Good grass establishment behind some terraces seeded to semidesert-adapted grasses. Based on six m^2 quadrats in bottoms of basins above terraces and five on intervening undisturbed areas between terraces.	Valentine 1947
Brush dams placed across slope between mesquite dunes. 12-16 inches high, tied down with wire ("Brush water spreaders").	Light grazing.	1937	Mesquite dunes with fourwing saltbush.	Loose sandy loam over compacted sandy loam, sometimes exposed at surface. Caliche at > 30 inches.		"… structures have brought about only the slightest improvement and this is restricted entirely to the areas immediately beneath the brush dams."	Valentine 1947

Treatment	Livestock Excluded?	Year(s)	Plant Community	Soil	Location (Pasture #)	Results	Source
Brush water spreaders. Brush held down at 2 foot intervals by wire ties anchored by driving knotted ends 10-12 inches into soil. Spreaders across slope, but trending downslope (1/2%). Water supplied from small dams across gullies. Seed scattered in brush of some seeders.	Yes (for at least 11 years) in one pasture. Light stocking in other pasture.	1937	Variable. Black grama. Black grama/tobosa. Creosote. Sparse fluffgrass with annual grasses and forbs.	Variable. Sandy loam (6-10 inches) over coarse sandy loam with one small area of compact clay loam.	N and E facing slopes 2-4% slope at foot of Dona Ana Mountains	“In general it is impossible to identify any area either above or below the spreaders that have been benefited from them”. Spreaders effective until dams broke after several years. Within 9 years, most water not diverted. Effective in creating microsites for seedling establishment. Noted patches of perennial grass establishment 8 years after construction. *Based on observations and five pairs of square meter quadrats located above and below spreader.	Valentine 1947
Crescent-shaped dams, contour furrows (at 10-20 foot intervals), check dams in gullies using grain sacks filled with soil and, in some cases, manure. Check dams were also constructed using	Yes	August, 1937	Creosote		North side of Dona Ana exclosure around 1915 black grama clipping	Heavy rains in September 1937 and summer, 1938 “… greatly damaged furrows and check dams”, but by the end of 1938, grasses had increased to 30% of total cover.	JER Staff 1939
Handgrubbing	n/a	1937-?	Tarbush	n/a	n/a	Substantial increase in forage yield by 1945.	JER Staff 1958
Lagomorph exclusion + Shrub removal + Seeding + Furrowing in a factorial design	Yes	1938	Creosote	Canutillo gravelly sandy loam (Dona Ana) Upton gravelly loam (Ragged and Parker tanks)	Dona Ana Exclosure (6) Gravelly Ridges Exclosure (20) Parker Tank (20)	1956: No effects of furrowing and seeding. Grass density increased in shrub removal plots and increased most in shrub removal + lagomorph exclusion plots. 1995: Increased shrub and grass cover in lagomorph exclusion plots. Increased black grama cover in shrub removal plots, but minimal no significant increase in total grass cover due to higher *Muhlenbergia porteri* in shrub-intact plots.	JER Staff 1958; Korzdorfer 1968; Gravelly Ridges only: Gibbens et al. 1993; Havstad et al. 1999

Treatment	Livestock Excluded?	Year(s)	Plant Community	Soil	Location (Pasture #)	Results	Source
Intensive contour structures and rabbit exclusion. 6 inches deep furrows located 4-6 feet apart, 8 inch deep furrows located 25-35 feet apart, 8 inch deep ridge contour furrows located 30-45 feet apart, 6 inch deep x 24-30 inch wide ripper furrows located 10-12 feet apart.	n/a	1939	Creosote, yucca, snakeweed, mesquite, fluffgrass and Croton corymbolus	Coarse sandy loam over coarse sand at 24 inches.	NE facing slope extending from foot of Dona Ana Mountains	No effect of contour structures on either perennial vegetation or soil moisture (measured to 24 inches), and no effect of rabbit exclusion.	Valentine 1947
Contour channels. Flat-bottomed trench along contour 24-30 inches wide x 6 inches deep with soil formed into ridges on each side by a road ripper with a piece of steel fastened to teeth. Intervals of 25-75 feet on 2-3% slope. 50-60 acres.	Yes	1939	Creosote, mesquite, snakeweed with scattered patches of bunchgrasses.	Loose sandy loam over caliche at 0-30 inch depth.	In Dona Ana exclosure near lagomorph exclusion study (?)	As a whole, the treated area is little if any different from the surrounding untreated area and it may be fairly concluded that the treatment has been ineffective in bringing about any improvement of the site.	Valentine 1947
Mesquite brush piles to capture Atriplex canescens seeds and improve microsite conditions for establishment in interspaces	Yes, in 1934	1939-1942	Mesquite dune	Onite (coarse-loamy, mixed Typic Haplargid)	Mesquite Sandhills Artificial Revegetation Exclosure (4)	Successful (1939). Unsuccessful (1942).	JER Staff 1958; Valentine 1942; Jornada Staff 1939
Mowing	n/a	1939-?	Snakeweed	n/a	n/a	"Gave some promise".	JER Staff 1958
Burning with a flame gun	n/a	1939-?	Snakeweed	n/a	n/a	Effective except when dormant.	JER Staff 1958

Treatment	Livestock Excluded?	Year(s)	Plant Community	Soil	Location (Pasture #)	Results	Source
Grubbing	n/a	1939-?	Snakeweed	n/a	n/a	Effective at all times of year.	JER Staff 1958
Mowing	n/a	1939-?	Snakeweed	n/a	n/a	"Gave some promise".	JER Staff 1958
Trenching to 26inches around dune interspaces + Cutting mesquite roots + Seeding grass, shrub and subshrub species	Yes, in 1934	1930's	Mesquite dune	Onite (coarse-loamy, mixed Typic Haplargid)	Mesquite Sandhills Artificial Revegetation Exclosure (4)	Only *Sporobolus spp.* and *Paspalum stramineum* emerged. None survived 5 years.	JER Staff 1958; Valentine 1942
Rodent, rabbit and livestock exclosures (various combinations). Design-limited: non-replicated and one treatment had 2.5X more grass at study initiation as other three.	See treatments	1940	Mesquite - snakeweed			1948 yield of "desirable grasses" dramatically higher in rabbit and rodent excluded plots in mesquite-snakeweed. Variable results in other 2 plant communities.	NM Ag Experiment Station 1949
Rodent, rabbit and livestock exclosures (various combinations).	See treatments	1940	*Erioneuron pulchellum*, *Aristida spp*.				NM Ag Experiment Station 1949
Rodent, rabbit and livestock exclosures (various combinations).	See treatments	1940	*Bouteloua*, *eriopoda*				NM Ag Experiment Station 1949
Seeding. Various attempts to plant native and exotic, including *Eragrostis spp*., *Bouteloua eriopoda, Sporobolus flexuosus and Atriplex canescens* using flat planting, furrow planting, loose seedbed and compacted seedbed.		1947-1949	Snakeweed and Creosote (2 sites)	"Good soil" and "Poor soil", respectively.	Various on CDRRC (College Ranch)	Poor to no establishment 1947, 1948 and 1949. In 1948, concluded that "success with about 50% of plantings is the best that can be expected".	NM Ag Experiment Station 1949; 1950
Handgrubbing areas averaging 30 mesquite plants/acre	Yes	1948	Black grama/ mesquite (1)		Artificial revegetation exclosures (?)	13.3% reinvasion after 7 years	JER Staff 1958
Hand grubbing areas averaging 805 mesquite plants/acre	Yes	1948	Mesquite/ bunchgrass (1)		Artificial revegetation exclosures(?)	64.5% reinvasion after 7 years	JER Staff 1958

Treatment	Livestock Excluded?	Year(s)	Plant Community	Soil	Location (Pasture #)	Results	Source
Hand grubbing areas averaging 30 mesquite plants/acre	Yes	1948	Black grama/ mesquite (1)		Artificial revegetation exclosures(?)	13.3% reinvasion after 7 years	JER Staff 1958
Railing	n/a	1952	Tarbush	n/a	n/a	Fair control in May.	JER Staff 1958
Contour terraces constructed with a road grader. Five, concentric, 3 inches high, on contour on a < 1% slope. Seeded and biosolids applied.	Yes, initially	1975-79	None			Experiment abandoned 8/79 due to repeated structural failure of dikes during heavy rain events and apparent lack of plant establishment. Resurvey in 1997 showed highly successful establishment.	Walton, unpublished data (JER)

(1) Grass component not specified; inferred from mesquite density.

Table 14-2. Longevity of remediation treatments visible in aerial (1936, 1947 and 1996) and satellite (1968, 1972 and 1983) photos in the Jornada Basin (modified from Rango et al. 2002). Y, P and N indicate that the treatments were visible, partially visible and not visible, respectively.

Treatment	Year Constructed	1936	1947	1968	1972	1983	1996
Contour terraces (A in Fig. 14.1a)	1935	Y	Y	Y	Y	P	P
Contour terraces (B in Fig. 14.1a)	1935	Y	P	N	N	N	N
Contour terraces (C in Fig. 14.1a)	1935	Y	P	N	N	N	N
Brush spreader (Fig. 14.1b)	1937	n/a	Y	Y	Y	P	P
Grubbed Strips (Fig. 14.1c-g)	1936	Y	Y	Y	Y	Y	Y
Exclosure 18 (Fig. 14.1h)	1939	n/a	Y	P	P	P	N

Seeding and Transplanting

Seeding and transplanting were generally done in association with one of the other treatments. A large variety of species were tried (Valentine 1942). Four-wing saltbush (*Atriplex canescens*) was one of the most popular species on sandy basin soils because of its value as a forage crop and its observed potential to compete with or at least coexist with mesquite. However, few of the treatments were successful. Valentine (1942) concluded that success depended on rainfall distribution and amount during the establishment period and during subsequent years. Many of the seedings in the artificial revegetation exclosure were planted in 1934, a year with barely half the average rainfall.

Microsite Manipulations

Manipulations designed to improve conditions for seedling establishment at the microsite scale (Fowler 1986) included piling brush (often cut from the top of mesquite dunes), digging trenches (to trap soil and seeds), and cutting roots (to reduce root competition from mesquite). Limited establishment was observed in response to these treatments and there was virtually no survival after five years (Valentine 1942). Seed burial was cited as a problem in many cases, particularly in the interdune areas.

Shrub Removal

Grubbing (shrub removal using hand tools) was frequently cited as one of the most effective approaches for maintaining or increasing the productivity of perennial grasslands. Attempts to combat shrub invasion by hand continued well into the second part of the twentieth century. As late as 1958, Herbel et al. concluded "grubbing light stands of young mesquite plants is the most economical means of controlling mesquite" (Herbel et al. 1958). At that time it cost $0.82 per acre to remove an average of 51 plants per acre. Careful examination of belt transects later showed that the grubbers missed 7% of the plants. Grubbing becomes more difficult as plant size increases because the root crown must be removed to prevent resprouting. Tarbush (*Flourensia cernua*) and creosotebush, relatively weak sprouters compared to mesquite were sometimes simply cut off at the soil surface.

Water Redistribution

Water redistribution was attempted at a variety of scales using both hand tools and tractor-mounted implements (table 14-1). In most cases, the objective was to slow the movement of water across the landscape through the creation of soil dikes, terraces, or furrows (figure 14-2).

Fig. 14-2. Aerial photo (1998) of contour dikes constructed in the 1970s showing vegetation establishment.

In at least one case, brush dams were constructed between mesquite dunes in areas with a gentle slope. Linear brush piles were also used to spread water from rock dams in gullies across creosotebush-dominated slopes.

Limited data available from a few plots showed only partial, if any, grass response to these structures by the mid-1940s (Valentine 1947). In a review of the water redistribution projects of the 1930s, Valentine (1947) reported that “In general it is impossible to identify any area either above or below the spreaders that have been benefited from them. This is true even of the area above the spreaders where the marks left by standing and running water give evidence that they were instrumental, at least occasionally, in bringing water to and holding it on these limited areas.” Interestingly, however, many of these treatment areas are visible six decades or more after their establishment due to higher grass or shrub cover and/or changes in species composition.

These long-term changes are often associated with a persistent shrub response to many of the water redistribution treatments. The concentration of even relatively limited quantities of water and nutrients on the contour terraces and behind the dikes could explain the apparently higher shrub biomass visible in figures 14-1 and 14-2. Valentine (1947) also observed that the brush water spreaders created more favorable microsites for seedling establishment. This observation is supported by Gutierrez-Luna (2000) who showed that water-dispersed seeds are preferentially deposited in naturally formed litter dams, and moisture and temperature conditions in these microsites tend to be more favorable for seedling establishment. Seedlings survive longer where there is litter on the surface.

Most of the water-retaining structures constructed during the 1930s were built on relatively coarse-textured soils with slopes > 2%. In at least one case in which soil moisture content was measured, the water-holding capacity of the soil was so low that no increase in moisture availability was detected behind the ridges (Valentine 1947). Additional water-retention structures were built in the 1970s on heavier soils with lesser slopes. Unlike the water-retention structures built in the 1930s, which were in shrub-dominated areas, the 1970s contour dikes were established in areas that were devoid of vegetation. The 1970s structures were abandoned within four years due to high maintenance costs and limited grass establishment in spite of seeding and sewage sludge applications. Twenty-two years later, however, native species had revived (Walton et al. 2001; see also figure 14-2).

These data, together with the fact that none of the water-retention structures constructed during the 1930s was maintained for more than five years, suggest that these strategies might be better viewed as being only partially tested rather than rejected as failures. In fact, some of the most vigorous grass patches on the Jornada are located upslope of the most carefully maintained water redistribution structure in the Basin: the access road that connects all of the CCC camps and the current NMSU and USDA headquarters to the city of Las Cruces. These patches extend up to 20 m upslope from the road, and there are a number of areas in which production is correspondingly reduced downslope.

Small Mammal Control

Work on small mammals was divided between attempts to control them using poisoned grain (for rodents) and poisoned salt blocks (for rabbits) and experiments designed to quantify their effects on grass production and survival. Valentine (1947) suggested that rodent and rabbit damage was one reason for the failure of brush dams to increase grass establishment between mesquite dunes. In 1939, jackrabbits (*Lepus*) and kangaroo rats (*Dipodomys*) were described as the “principal range-destroying rodents” which were “controlled by shooting and poisoning” (JER Staff 1939). Data from three replicated lagomorph exclusion experiments show that over a 28-year period, perennial grass cover was on average higher at two locations and that there was no significant effect of exclusion at the third location (data from Korzdorfer 1968; ANOVA; n = 8 for each site; p = 0.02, 0.09, and 0.31). Data collection continued at one of the locations where in 1967 basal cover was close to zero in nearly all plots. By 1995, cover at this one location had rebounded to 3.5% in lagomorph-excluded plots and 2.9% in the plots to which rabbits had free access (Havstad et al. 1999). This experiment is unique in that it is one of the oldest manipulative experiments (other than livestock exclosures) replicated at the landscape scale.

The successful efforts to remove prairie dogs (*Cynomys ludovicianus*) from the basin in 1916–17 and the unsuccessful attempts to eradicate kangaroo rats were part of early remediation attempts and were apparently based on the assumption that these animals competed extensively with livestock for forage (chapter 12). Confidence in the efficacy of the eradication treatments was low, as illustrated by the fact that rodent and rabbit exclosures designed to quantify the impacts of small mammal herbivory in an artificial (seeded and transplanted) revegetation experiment were established near the center of a 9-square-mile area in which poison baits were repeatedly applied (table 14-1). While small mammals reduce perennial grass density near their burrows and increase the wind- and water-erodible soil and in unvegetated patches (chapter 12), they also remove shrub seedlings and are important seed dispersal agents that may actually contribute to future remediation strategies (Havstad et al. 1999). For example, Gibbens et al. (1992) reported that 81% of mesquite seedlings emerging in response to a July 31, 1989, rainstorm were dead by the following May. Of these, all but 2% had been bitten off "at or slightly below the cotyledonary node, which causes death." All of the surviving seedlings also showed signs of herbivory.

The Promise of Technology (1941–1980s)

The apparent failure of grazing management alone to reverse the shrub invasion of grasslands, together with the uncertain effectiveness of the Depression-era manipulations led to an intensified search for viable alternatives that could be applied with minimal labor. During the boom years following the war, fossil fuels replaced human labor as the most cost-effective input and “shrub control” became the new mantra. The authors of the 1958 annual report for the JER observed that “there is no evidence of recovery [of mesquite sand dunes to grassland] after 25 years, even in areas completely protected. To the contrary, severe duning has been spreading even with conservative grazing . . . the absence of grazing use will not retard that spread…The suggested control method is “grubbing” (JER Staff 1958).

The reduced emphasis on water redistribution-based approaches attempted during the 1930s was probably driven in part by the absence of any evidence of positive impacts of these approaches during the drought of the 1950s, when annual precipitation (from 1950–56) averaged just 150 mm/year. Although there are few quantitative records of the effects of the Depression-era treatments, the quadrat studies (Gibbens and Beck 1987) and shrub removal/lagomorph exclusion experiments suggest that grass recovery in response to management was virtually erased during the accelerated loss of grassland during the 1950s drought. Attempts to control water distribution did continue, however (table 14-1), and the development of new equipment allowed for more labor-efficient if not more effective resource redistribution.

Herbicides

Herbicides offered the opportunity to reduce shrub competition without disturbing the soil surface. With the virtual disappearance of inexpensive labor in the boom years of the 1950s, shrub control methods that could be applied to large areas with minimal human effort were in high demand.

Early Trials

Herbicide studies were initiated in the 1930s. Plants were sprayed with sulfuric acid, kerosene, sodium chlorate, and diesel oil and dusted with mixtures of borate and sodium chlorate. Only sodium chlorate and atlacide (a chlorate-based material) were effective in trials with snakeweed (*Gutierrezia sarothrae*) and only at concentrations in excess of 10% (JER Staff 1958). In the 1940s a number of materials were injected into the soil at the base of mesquite plants. The only material that was consistently successful was a mixture of diesel oil and 10% ethylene dibromide (New Mexico Agricultural Experiment Station 1949).

Synthetic Herbicides

The development of phenoxy herbicides, specifically (2,4,5 – trichlorophenoxyacetic acid) 2,4,5-T, after World War II opened a new era in shrub control. These materials could be applied aerially over large areas and, with timely application, could result in significant reductions in shrub productivity and density. Although 2,4,5-T can no longer be legally applied to rangeland, there are a number of other materials, including clopyralid, tebuthiuron, and monuron, that are still available. Shrub density has been successfully reduced on relatively large areas in the Chihuahuan Desert in both the United States and Mexico, and herbicide applications are frequently included in brush management plans. Much of the remaining grassland on the JER and the Chihuahuan Desert Rangeland Research Center (CDRRC) has been treated at least once with herbicide.

Management recommendations for the use of these herbicides based on several decades of research are summarized in a New Mexico State University Agricultural Experiment Station Bulletin (Herbel and Gould 1995). Even this relatively optimistic publication, however, concludes with the cautionary note that “it is possible to renovate brush-infested rangelands with herbicides, but some of the practices are costly.” The practices, including both seeding and the herbicide applications themselves, frequently must be reapplied several times (Ethridge et al.

1997). Economic limitations often limit their use to more productive sites or to sites that have multiple values, such as watershed protection and wildlife habitat conservation (Bovey 2001). Although there are many herbicides available, those that were most toxic to animals or caused other environmental problems have been taken off the market. The environmental costs of rangeland herbicide applications continue to be of concern in some areas (Bovey 2001).

Mechanical Treatments

Numerous implements were designed by engineers to exploit the ever increasing power of agricultural and engineering machinery to remove shrubs, prepare a seedbed, create small pits where water could accumulate, and plant seeds. The Arid Land Seeder accomplished all four operations in a single pass. Developed at the JER and tested during the 1960s (Abernathy and Herbel 1973; Herbel et al. 1973), this implementation consisted of a standard root plow mounted on a bulldozer trailed by a conveyor assembly and rangeland drill. Brush was removed by the root plow, carried by the conveyor assemble over the top of the drill, which planted the seed, and replaced the brush over seeded rows to form a mulch over the seeds. Various modifications of the machine were used to clear and seed 23 plots dominated by creosotebush and/or tarbush between 1966 and 1970. The plots were each approximately 2 ha in area and were scattered throughout southern New Mexico. Approximately 50% of the seedings were considered successful based on qualitative evaluations made six years or sooner after treatment (Abernathy and Herbel 1973). Drought was cited as the primary reason for failure, with overgrazing of recently established grasses also contributing (Herbel et al. 1973). Other devices used to remediate Southwestern rangelands, especially in southern Arizona, are summarized in Jordan

(1981) and Roundy and Biedenbender (1995). Some of these approaches were also tested in the Jornada Basin (JER Staff Annual Reports unpublished).

All of these treatments result in high levels of soil surface disturbance, increasing erosion susceptibility (Wood et al. 1991). They also require significant energy inputs and the availability and maintenance of expensive machinery. They can, however, be effective in reducing shrub density and cover. Following an evaluation of 92 years of reseeding efforts in the Southwestern United States and Mexico, Cox et al. (1984) concluded that although most of the approaches evaluated were at least occasionally successful, “no single seedbed treatment has been shown to be superior to any other over time.” It was also concluded that reseeding studies needed to be conducted more systematically.

Comparisons of the relative cost and effectiveness of mechanical versus chemical shrub control have yielded variable results. Tebuthiuron was generally more effective at reducing creosotebush canopy cover and increasing forage production at four sites in the Chihuahuan Desert of southeastern Arizona and northern Chihuahua, Mexico (Morton and Melgoza 1991). Holechek and Hess (1994) estimated that burning cost $1–5/acre (where sufficient fuel exists), herbicide cost $12–20/acre, and mechanical control cost $25–50/acre. Estimates include the cost of materials, machinery depreciation, and labor.

Ethridge et al. (1997) found that only 1 in 10 rangeland seedings in southern New Mexico was profitable when the costs were compared to income from increased livestock production. Jones and Johnson (1998) pointed out that some of the failures may have been unnecessary as, “sophisticated analyses of ecological adaptation and genetic variation were rarely considered in early trials.” In other words, at least some of the failures may be partially attributed to the seeding of species and varieties that were not adapted to the local edaphic and climatic conditions. However, many of the failures were clearly due to inadequate soil moisture and the rapid reestablishment of shrub species.

Other Technologies

A number of other technologies have been tried, ranging from applying hot wax to increase runoff from mesquite dunes (Gibbens personal communication) to using polyacrylamide to reduce soil crust resistance to seedling emergence and increase infiltration capacity. Greenhouse trials indicated that polyacrylamides may effectively increase seedling emergence (Rubio et al. 1992); however, the results of the infiltration studies were inconclusive (Rubio Arias 1988).

Data Quality and Reliability of Conclusions

Experimental designs varied widely. Most of the studies were not replicated and baseline data were frequently not recorded or were recorded on such small plots as to be of little value. Many studies for which there is some baseline information have been unreplicated, and in many cases, the most useful information is qualitative.

In spite of these caveats, these studies in aggregate represent a tremendous resource. They addressed, either directly or indirectly, virtually every factor potentially affecting grass establishment and survival. Many of the treatments were applied in logical combinations in an attempt to remove multiple constraints (brush mulches combined with water redistribution or reduction in rodent or rabbit populations). The treatments were often replicated across the landscape and applied during different years, providing a nonstatistical but potentially more relevant form of replication. The discussion summarizes a relatively small fraction of the work completed. Although many records no longer exist, others persist in archives scattered throughout the country. One of the reports cited (JER Staff 1939) was found at the National Agricultural Library in Washington, D.C., but had obviously been rescued from the USFS Allegheny Forest Experiment Station library, which stamped it “March 13, 1939, RECEIVED.” Our ability to interpret the long-term impacts of the historic treatments will continue to increase as we relocate and resample them using a combination of historic and contemporary aerial photographs, ground-based rephotography, and on-ground surveys, together with the archival records cited here.

Summary

Four generalizations can be drawn from the historic literature. The first is that most past attempts to manipulate the system failed. The second is that there are enough successes to convince some, at least, that the system can be controlled (Cassady and Glendening 1940). The third is that it often takes decades to determine the success or failure of a particular manipulation. It may take decades for positive effects to appear as plant-soil feedbacks gradually change soil water-holding and infiltration capacities. Meteorological conditions that facilitate establishment occur relatively rarely and may be poorly timed relative to other factors affecting establishment, such as the number of germinable seeds in the soil and herbivore population dynamics. Conversely, short-term successes can rapidly turn into failures as landscape-level processes gradually overwhelm patch-scale treatments and droughts that cause widespread mortality among long-lived perennial plants occur just once every several decades. The fourth, and perhaps most important generalization, is that the success or failure of a manipulation depends on multiple interacting factors. The relative importance of each factor varies across space and time.

Understanding Ecosystem Processes

Until the start of the International Biology Programme (IBP) in 1970, most research in the Jornada Basin was specifically designed to determine which treatments could be used to improve management. Over the past three decades, emphasis on improving understanding of basic ecosystem processes has increased. The objectives of the research vary and, in some cases, continue to be management-driven. Increasingly, however, it is recognized that the success of future management systems will depend on a more thorough understanding of these processes, and it is not always obvious which need to be studied. In many cases, the most obvious process is not necessarily the most important one. Chesson and Huntly (1997) argue that species coexistence is favored by harsh but fluctuating conditions that create opportunities for establishment that vary through space and time.

In 1986, Wright and Honea concluded the abstract of an article on soil properties in mesquite dunelands with the statement, “It seems as if the entire set of changes in the soil environment . . . ensure that mesquite will occupy those sites for long periods of time.” The changes include soil organic matter, nitrogen, cations, phosphorous availability, and soil texture, particularly where there is an argillic or other horizon with a texture different from that at the soil surface (figure 14-3). It has also been shown that the effects can persist long after shrub removal. Thirteen years after velvet mesquite (*Prosopis juliflora*) removal, canopy–interspace differences in soil carbon were virtually identical to those where mesquite had been left intact at a site in southeastern Arizona, which has slightly higher temperatures and winter rainfall than the Jornada Basin (Tiedemann and Klemmedson 1986).

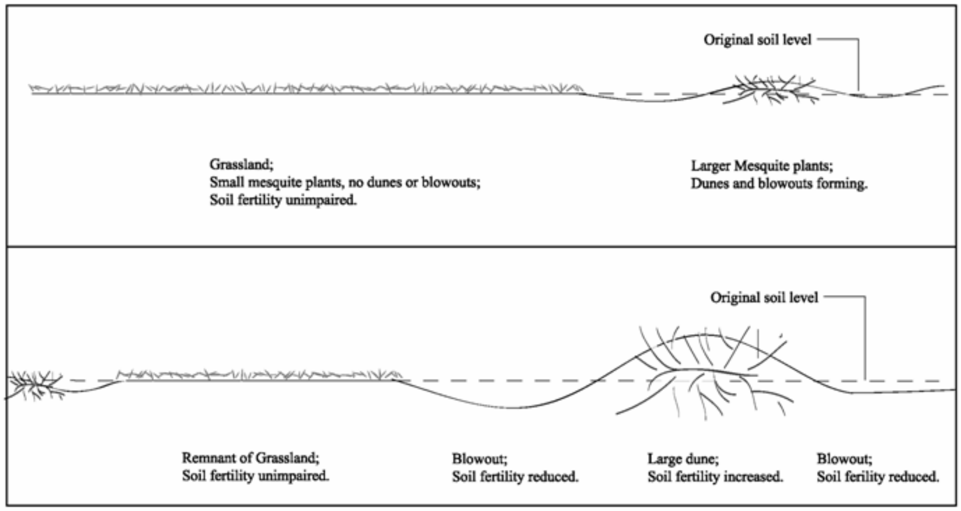


Fig. 14-3. An early representation of the fertility changes associated with mesquite *(Prosopis glandulosa)* invasion (Valentine 1941).

Schlesinger et al. (1990) describe a framework for understanding how various processes combine to reinforce the grass–shrubland transition. This framework, together with the landscape-level dynamics currently being addressed by the research program in the Jornada Basin, can serve as a starting point for defining the types of interventions that are most likely to be successful and identifying the parts of the landscape and times (relative to drought, extreme precipitation events, and fluctuations in herbivore populations and seed banks) when grassland recovery is most likely to occur.

Schlesinger et al. (1990) also highlighted the importance of the formation, maintenance, and deterioration of resource islands in deserts throughout the world. Studies in Israel (Boeken and Shachak 1994),[a], and Australia (Tongway and Ludwig 1997), as well as the United States (Valentine 1941; Schlesinger et al. 1996; Wainright et al. 1999b), have addressed the mechanisms by which human- and vegetation-formed patches affect plant production and

[a] Dixon and Simanton 1980 not found in the Refs list for the book. Please add it. Deleted

resource availability and redistribution at multiple spatial scales. This trend toward understanding the processes responsible for the patterns should help target those processes that limit the success of remediation attempts.

Understanding the importance of resource redistribution at the plant-interspace level generated by the Jornada Basin research has led to a renewed interest in the possibility of manipulating resource availability to trigger changes in vegetation composition and structure. Most now agree that one of the keys to the persistence of shrublands in spite of diverse efforts to remove them is their ability to acquire resources from both greater depths and larger areas than grasses and to concentrate and retain those resources in self-reinforcing islands of fertility (figure 14-3; Valentine 1941; Wright and Honea 1986; Schlesinger et al. 1990). The key to maintaining production during drought years is the ability to tap deep water, while extensive shallow-root systems allow shrubs to compete with grass for water from brief or low-intensity rainstorms (Gibbens and Lenz 2001). The effect of reduced nutrient availability on grass production in mesquite dune interspaces was documented over 60 years ago (Valentine 1941).

Landscape-level controls on recovery are also clearly important, though less well understood. The importance of long-term geomorphic stability and inherent edaphic characteristics (McAuliffe 1994) has been clearly demonstrated and must be considered together with resource redistribution patterns (chapter 7) in predicting which parts of the landscape are most likely to respond to management inputs.

The Landscape Context: Edaphic Controls on Resource Availability

McAuliffe (1994) documented strong relationships between soil development and vegetation in southeast Arizona. Similar relationships have been reported for the Jornada (chapters 2 and 4).

Perennial grasslands tend to persist on soils with an argillic horizon near but not at the soil surface. Argillic horizons are rich in clay and tend to retain more water at a depth that is accessible to grass roots. These soils tend to be located on older, more stable surfaces (as argillic horizons take thousands of years to develop). Similar patterns have been documented in the Chihuahuan Desert. Where black grama grasslands persist on coarse-textured soils in the Jornada Basin, there is often a calcic or petrocalcic horizon near the soil surface (Teaschner 2001). Highly developed calcic horizons appear to be relatively impervious to both water and roots. Most of these horizons, however, are heavily invaded by roots and have higher water-holding capacity than the loamy sands typical of many Chihuahuan Desert basin soils now dominated by mesquite. The failure of at least one intensive effort to increase grass establishment by concentrating water was attributed to the fact that the water-holding capacity of the soil was too low to support grassland (Valentine 1947).

The Landscape Context: Geomorphic and Climatic Stability

Geomorphically stable surfaces are necessary for the development of many of the soils that appear to have the greatest resistance to shrub invasion, such as those with an argillic horizon or a near-surface calcic or petrocalcic horizon (McAuliffe 1994). The amount of time required for recovery of some plant communities may be longer than past periods of geomorphic (and climatic) stability (Webb et al. 1987). The importance of lag time between climate and plant community changes associated with soil-vegetation feedbacks is poorly understood. Continuing soil erosion in shrub-invaded areas may effectively reduce the proportion of the landscape within which recovery of pre-1850 plant communities is possible or at least dramatically increase recovery time (Coffin Peters and Herrick 1999). The ultimate effects of soil degradation and loss on establishment probabilities for different species also depend on climate change and, particularly, precipitation amount and seasonal distribution.

The Landscape Context: Resource Redistribution

Identification of the scale at which resource redistribution affects plant community dynamics is critical to developing ecologically based approaches to remediation. This issue, which is now being addressed by Jornada researchers, is very poorly understood and is defined as one of our research objectives. We know that during most precipitation events, the majority of water redistribution occurs at the plant-interspace scale. We also know that some plant communities, such as those in playas, rely on larger, rarer events that result in water redistribution at the landscape scale. We do not understand how changes in the intensity and frequency of these redistribution events affect plant establishment, production, and survival at the two scales. We know even less about the effects of nutrient redistribution at multiple scales.

Similar issues apply to the dissemination of seeds, a key resource that can be quickly depleted through granivory and germination (Peters 2003). The maintenance of many plant communities depends on local seed production, whereas species invasions can be promoted through both short-distance dispersal along ecotones and long-range dispersal from distant populations. Seed banks represent yet another form of dispersal, but in time instead of space.

The relative importance of these three dispersal mechanisms for shrub persistence and grass reestablishment needs to be defined as part of any attempt to reestablish grassland in currently shrub-dominated systems. W. G. Whitford (personal communication) estimated that honey mesquite *produced* over 100 seeds per square meter in a mesquite-dominated community based on seed and pod counts. Tschirley and Martin (1960) reported that 9% of originally germinable seeds of the congeneric velvet mesquite were still germinable 10 years after burial at the Santa Rita Experimental Range in southeast Arizona. However, mortality can also be quite high. One study showed that less than 1% of seed produced remains in the seedbank one year after production with insect damage accounting for most of the mortality (Owens unpublished data). Mesquite seeds are dispersed over relatively short distances by rabbits and other small mammals and over longer distances by livestock (Tschirley and Martin 1960).

Fire: A Missing Link

Our understanding of one of the most fundamental agents of change in many ecosystems—fire—is extremely rudimentary, particularly when compared to our understanding of its role in forested and more mesic grassland systems (Knapp et al. 1998). Fire has been used in more mesic areas to both manage the growth form of mesquite (Teague et al. 1997) and prevent mesquite encroachment. There is some evidence to suggest that fire may be used in the Chihuahuan Desert to limit shrub expansion if it is applied during a relatively wet year when grasses can recover. The effects of a burn in most systems depend on careful timing relative to current weather, soil moisture, fuel load, and the size and growth stage of both the herbaceous and woody components (Drewa and Havstad 2001). These factors can all be measured or predicted with a relatively high level of confidence. In systems in which precipitation is low and unpredictable, however, one of the most important factors is also among the least predictable: the weather conditions following the fire. Long periods without precipitation following a fire can result in increased erosion and mortality of the less deeply rooted grasses and perennial forbs. In addition, seldom do fuel loads on the northern Chihuahuan Desert meet minimum levels of 600 kg/ha that have been recommended by Wright (1980) for desert grasslands.

Results of two sets of experiments in mesquite-invaded, black grama grasslands showed that fire reduces mesquite shrub volume but does not result in shrub mortality. Four years following fire in 1995, perennial grass cover was 13% lower in burned 8 × 12 m plots and 5% higher in unburned plots, and frequency decreased 30% in the burned areas compared to a 10% increase in unburned areas (Drewa and Havstad 2001). Black grama mortality was 45%, 27%, and 19% for small, medium, and large clumps one year after a 400-ha burn in 1999, compared with 11%, 4%, and 3% in 4-ha unburned controls. Fire conditions were nearly ideal with high winds during the May fire immediately followed by unseasonably early rains in June. Shrub volumes declined 40% in the burned areas and increased 30% in the unburned controls, but there was little evidence of shrub mortality (Drewa et al. 2001). The results of both studies together with the relatively high costs of propagating fire in these patchy arid environments imply that although fire may help slow shrub invasion, benefits, costs, and potential risks should be carefully considered before application to large areas.

Future Scenarios

Restoration of native grasslands and other plant communities may be limited by one or more of the following factors: (1) invasion of highly competitive, persistent species; (2) loss (both documented and undocumented) of plant, animal, and microbial species from the system; (3) loss of soil and/or modification of dynamic soil properties; (4) infrequency of suitable establishment periods with adequate soil moisture; (5) landscape level processes that overwhelm small-scale manipulations; and (6) those sites that are the most resilient will not necessarily be the most resistant to future degradation. Successful strategies in the future will need to address each of these limitations. We also need to find indicators that can be used to predict future trends in systems in which persistent changes in perennial vegetation may not appear for decades. To increase the probability of success, we need to focus more on restoring the resistance and resilience of soils and plant and animal communities rather than on short-term similarities to a particular community structure or composition.

Future success will also depend on recognizing that neither the soils nor the climate nor the faunal community are the same today as they were during the latter part of the nineteenth century when shrub invasion into grasslands began to accelerate. They are likely even more different than they were when the perennial grasslands became established. Loss of soil and animal species and additions of new species to the system, together with climate change, may mean it is no longer possible to reestablish some plant communities or that it may be possible to reestablish them only in selected parts of the landscape.

Figure 14-4 illustrates one possible approach to future remediation in which limited inputs are targeted to parts of the landscape with a high potential for change, triggering change at that site and, ultimately, change in the surrounding area (Herrick et al. 1997).

A first step to identifying these high-potential areas is to eliminate areas from consideration that have clearly crossed a threshold beyond which recovery is unlikely (Chambers 2000). Similar ideas are described in greater detail in Whisenant (1999). Based on historic documents, the concept was familiar to Jornada scientists in the 1930s.

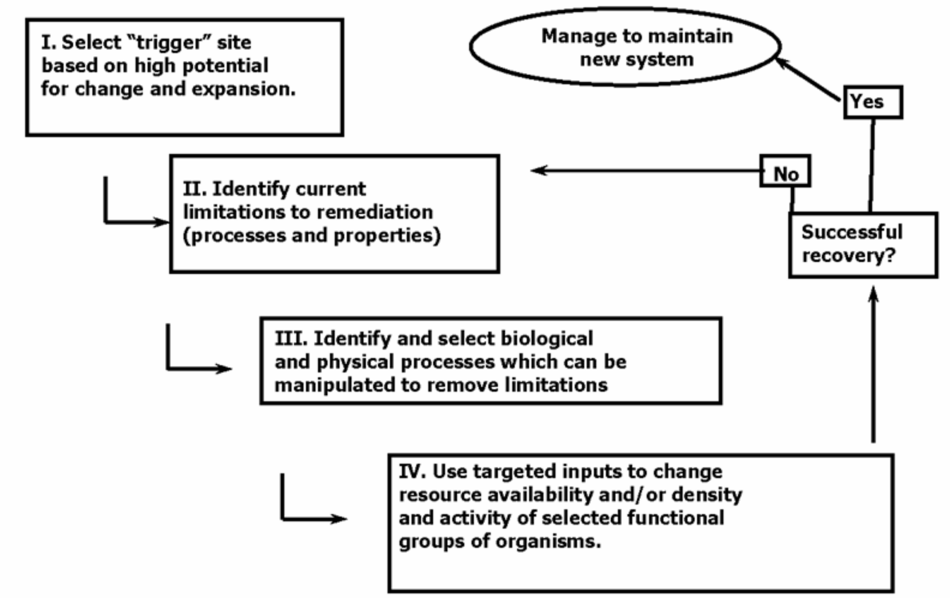


Fig. 14-3. An early representation of the fertility changes associated with mesquite *(Prosopis glandulosa)* invasion (Valentine 1941).

The authors of a 1939 report argued that although many of the intensive revegetation approaches "would be uneconomical for general application . . . certain key or strip areas could be so treated on the basis that the entire area would in time be improved by natural spread from the treated portions" (JER Staff 1939). The concept of targeting areas with naturally higher resource availability was resurrected by Herbel (1982) in a proposal to focus herbicide-based brush control on run-in areas, while leaving shrub-dominated upland areas to produce runoff. The argument was based both on the low benefit-cost ratio for treating the upland, runoff-producing areas, the higher returns for the run-in areas, and the recognition that maintaining runoff from the upland areas could be used to increase production on the lower areas.

It would appear from the location and design of some of the historic treatments, however, that the trigger site approach was tested numerous times during the 1930s. And it failed. The selection of potential trigger sites may be improved with technology and an enhanced understanding of processes operating at multiple scales. Nevertheless, comments in the historic records, supported by our observations and recent landscape-level analyses (see chapters 2 and 4) suggest that application of the trigger site concept is limited by loss of native species, historic soil degradation, potential threats of invasive species, and the infrequency of suitable establishment periods. It is also potentially limited by the tendency for both native and domesticated herbivores to converge on areas with the highest quality forage, as illustrated by rabbit pellet and cattle dung patch counts in small patches (less than 5 ha) in which perennial grasses have been successfully established (Fuhlendorf and Smeins 1997).

The relative importance of resistance and resilience also needs to be considered. Sites that are most resilient are not necessarily most resistant to future degradation (Seybold et al. 1999). Degraded riparian zones in the Southwestern United States, for example, recover relatively quickly compared to upland systems when livestock, and sometimes elk, are excluded except when invaded by salt cedar. However, remediated systems are often not very resistant to subsequent overgrazing until the woody species have grown beyond the reach of livestock, though much of the research in this area is anecdotal (Sarr 2002). For example, the location of riparian sites in lower parts of the landscape also makes them susceptible to more intense flooding caused by upslope watershed degradation than they would have experienced before they were degraded. In this case, their resistance may have recovered; but a change in the disturbance regime (flooding) may affect their ability to function as they did before the uplands were degraded.

All of these limitations can potentially be overcome through a combination of: (1) careful analysis to identify the factors and processes that are most likely to limit establishment and survival at a particular time and location; (2) patience and a flexibility to initiate interventions when they are most likely to be successful, rather than when funding and logistical support are available; and (3) attention to landscape-level controls. Creative integration of multiple approaches, including short- and long-term experiments and monitoring, gradient analyses and descriptive studies, and conceptual, empirical, and theoretical modeling, will be necessary to develop effective remediation strategies based on an understanding of key ecological factors and processes (Archer and Bowman 2002).

Relevance to the Southern Chihuahuan Desert and Other Deserts

The basic patterns and processes described here are similar to those described for many other parts of the world. Roundy and Biedenbender (1995) draw similar conclusions based on their review of literature primarily focused on Arizona. Ballín Cortés (1987) identified a similar suite of limitations to the recovery of ecosystems in his analysis of desertification in the southern Chihuahuan Desert at approximately 21° N latitude. Lovich and Bainbridge (1999) concluded their assessment of the potential for restoration of southern California deserts by stating that "restorative intervention can be used to enhance the success and rate of recovery, but the costs are high and the probability for long-term success is low to moderate." The recommended strategy for the future is similar to that proposed by Whisenant (1996) and Tongway and Ludwig (1997), based on their experiences in central Texas and Australia, respectively.

Conclusions

Early investigators had an intuitive and practical understanding of the system in which they worked. They saw the individual limitations to grassland recovery and attempted to address them. To be more successful than they were, we must begin to work at spatial and temporal scales that are relevant to the processes we hope to affect and target interventions to those locations during those periods when the processes are most susceptible to change. We must also, as the earlier workers did, simultaneously target multiple processes with the objective of increasing the resistance and resilience of the modified ecosystems.

Socioeconomics and Research Psychology: A Footnote

The role of societal values in defining remediation objectives and of economics in defining restoration success has been referred to several times in this chapter: remediation efforts through the 1980s were primarily designed to produce more forage for livestock (a societal benefit) and to reduce soil erosion (a cost). The success of remediation efforts, however, has been generally defined usually in terms of the net economic benefit to livestock producers. Evolution of societal values, human population growth, and the associated redistribution of financial resources will inevitably lead to shifts in the ways that costs and benefits of remediation efforts are evaluated.

At a deeper level, social and political values help define how ecologists view ecosystems, what we decide to emphasize in our research, and how we describe the results of our research. In some cases, the relationships are direct: Societal interest in restoring or maintaining grasslands to reduce soil erosion to improve air and water quality or to produce more livestock forage explain why we know much more about how to establish exotic grasses than native sagebrush in the Great Basin (Young et al. 1981). In other cases, there is a more subtle effect on where ecologists look first for answers to explain the success or failure of an intervention. For example, there is an ongoing debate on the relative importance of changes in root versus fungal biomass (Hodge 2001). Both are difficult to measure accurately, and biases can easily result in the selection of measurements, techniques, or levels of replication that favor one variable over another.

Finally, research is expensive, and it is neither intellectually nor logistically possible to consider all possible variables simultaneously. The successful future application of basic and applied ecological research to remediation depends on the ability and willingness of ecologists to include a discussion of the assumptions and potential biases that drove the selection of the research questions, experimental design, and interpretation of the results. Failure to do so may result in a repetition of the past in which single- or dual-factor treatments applied at a single location and single point in time were overwhelmed by complex interactions, many of which remain unidentified or at least unquantified.