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Remote sensing documentation of historic rangeland remediation treatments in southern New Mexico

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The Jornada Experimental Range and the New Mexico State University Chihuahuan Desert Rangeland Research Center are fruitful areas to study the long-term effects of rangeland remediation treatments which started in the 1930s. A number of diverse manipulations were completed under the direction of federal agency and university scientists, and abundant remote sensing imagery is available to assist in relocating the treatments and evaluating their success. This is particularly important because few of the treatments were maintained following the loss of scientific personnel coinciding with the start of World War II, and most records of Civilian Conservation Corps scientific work were lost with the disbanding of the agency in 1942. Aerial photography, which was systematically used to image the United States beginning in the 1930s, can be used to identify types of treatments, measure areal coverage, estimate longevity, and help plan locations for new experiments. No long-lasting vegetation response could be determined for contour terraces, brush water spreaders, strips grubbed free of shrubs (despite the fact that these strips have remained visible for 65 years), and mechanical rootplowing and seeding. Distinct positive, long-term vegetation responses could be seen in aerial photos for water retention dikes, certain fenced exclosures, and some boundaries where different land management practices meet. It appears from both aerial photos and existing conventional records that experimental manipulation of rangelands has often been ineffective on the landscape scale because treatments are not performed over large enough contiguous areas and hydrological and ecological processes overwhelm the treatments. In addition, treatments are not maintained over time, treatment evaluation periods are sometimes too short, multi-purpose

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treatments are not used to maximize effects, and treatments are often not located in appropriate sites.

Keywords: rangeland remediation, remote sensing, aerial photography, shrub removal, water spreading, new Mexico

Introduction

Rangeland makes up 50–70% of the world's landmass (Holechek *et al.*, 1995). According to Holechek *et al.* (1995), rangeland is defined as uncultivated land that will provide the necessities of life for grazing and browsing animals and therefore includes deserts, forests, and all natural grasslands. The amount of arid and semi-arid lands on the earth's surface ranges from 33 to 43% of the total land area depending on whether the classification is based on drainage effectiveness, vegetation, climate, or soils (Walton, 1969). For practical purposes, most of the arid and semi-arid land is rangeland which means that well over 50% of the world's rangeland is also arid or semi-arid. Whether the objective is to have a highly productive range for livestock grazing or to enhance biodiversity, improve ecosystem health, produce high-quality water or sequester carbon, rangeland areas are extremely valuable and worth preserving in optimum conditions. Since about 1850, shrubs has been displacing grasses on south-western U.S. rangelands and resource scientists have made numerous attempts to rehabilitate degraded rangelands and reverse the trend toward shrub domination. The need for such attempts has been evident all over the south-west since the early 1900s (Griffiths, 1901), and it was reported by Wilson (1931) that degraded rangelands of the south-west were beyond natural recovery. With the creation of the Civilian Conservation Corps (CCC) in 1933, significant human resources became available which could be directed to attempts to rehabilitate degraded rangelands. The CCC camps in New Mexico provided 50,000 young men for various types of productive work (including rangeland rehabilitation) in the state (Melzer, 2000). Although this agency's labor-intensive activities ended with the disbanding of the CCC in 1942, efforts to treat degraded rangeland with new technologies continue through the present day.

In south central New Mexico, the Jornada basin (about 37 km north of Las Cruces) is an ideal area to study historic rangeland remediation treatments. The Jornada basin is located between the Rio Grande floodplain (elevation 1186 m) on the west and the crest of the San Andres Mountains (2833 m) on the east. Located in the basin are two long-term rangeland research sites. The Jornada Experimental Range (JER) of the U.S. Department of Agriculture (USDA) was established in 1912 under the jurisdiction of the Bureau of Plant Industry, transferred to the U.S. Forest Service in 1915, and finally to the Agricultural Research Service (ARS) in 1954. The JER encompasses 783 km^2, making it the largest ARS field station. Adjacent to and south-west of the JER is the New Mexico State University Chihuahuan Desert Rangeland Research Center (CDRRC), formerly known as the New Mexico Agricultural Experiment Station College Ranch, or simply the College Ranch. The CDRRC was given to the State of New Mexico in 1927 by Congress and covers 259 km^2. The Jornada Basin Long-Term Ecological Research (LTER) program was begun in 1982 under the auspices of the National Science Foundation, and LTER studies are located on both experimental ranges. Figure 1 shows the relative locations of the JER and CDRRC along with specific locations of LTER and other research sites in the Jornada Basin. Both the JER and CDRRC had significant CCC rangeland rehabilitation activities in the 1930s under the direction of rangeland scientists from the Forest Service, Soil Conservation Service, New Mexico A&M College (now New Mexico

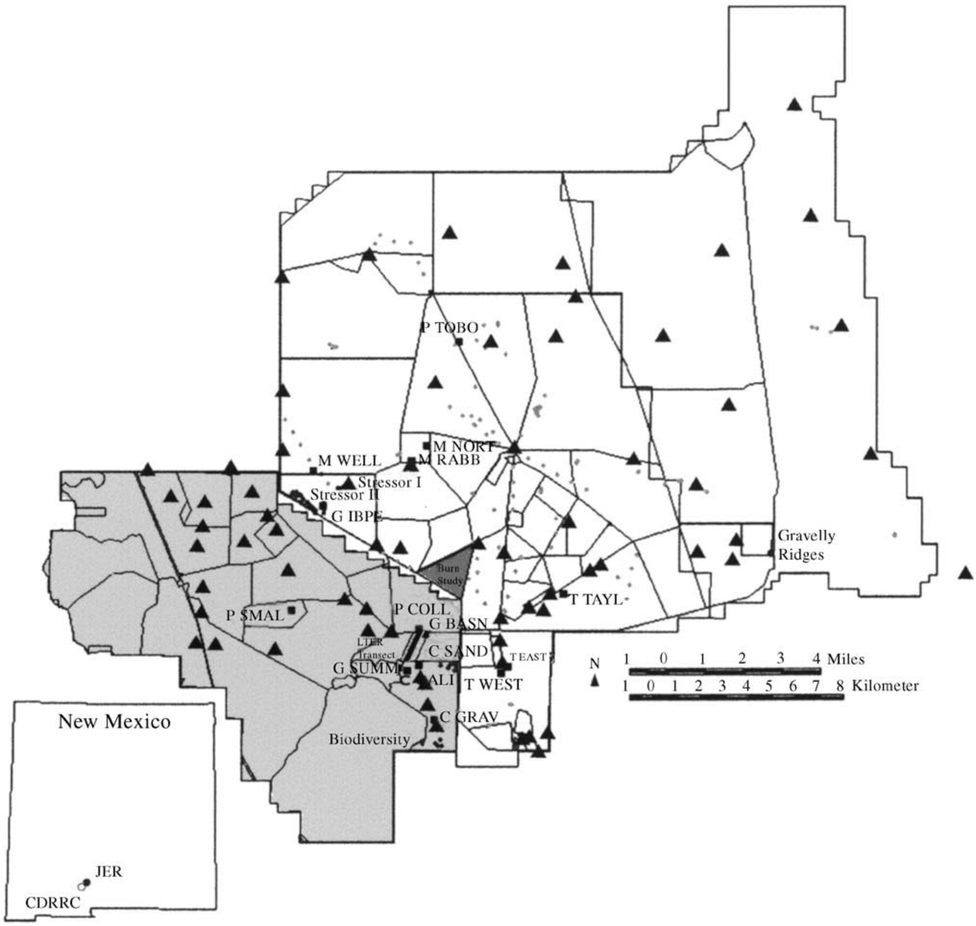

Figure 1. Location of the Jornada Experimental Range (JER) (783 km^2) and the New Mexico State University Chihuahuan Desert Rangeland Research Center (CDRRC) (259 km^2) experimental ranges and sites for long-term studies: ▭, Jornada Experimental Range; ■, Chihuahuan Desert Rangeland Research Center; ▲, Raingauges; ▬, LTER Transect; ■, Net primary production; ●, Permanent quadrats.

State University) and other associated agencies. In fact, as many as four CCC camps were located on JER and CDRRC lands.

Although remediation treatments were numerous in the 1930s, it is generally difficult to find out precisely what was done and where, and what were the specific objectives of treatments. Experiments were poorly documented because several different agencies were involved. Although they supplied labor for the remediation treatments, the CCC apparently kept few records on the scientific objectives of their activities, and most records that were kept have been lost since the CCC's disbanding in 1942. The CCC, with co-operation of personnel from the land management agencies, did publish a series of conservation reports, and two of them dealt particularly with rangeland rehabilitation (Bailey & Croft, 1937; Cassady & Glendening, 1940). These reports document the kinds of treatments put in by the CCC, but do not deal with specific areas to any great degree.

Records of the other agencies regarding the rangeland treatments applied are not especially good either. Most references made to the treatments are of a very general nature. Compounding this lack of specificity is the possible disposal of old records in periodic cleanup activities. Much of the specific documentation needed to pinpoint the exact nature of the remediation efforts was either lost or never recorded to begin with. It is possible that documentation was planned to be completed after the treatments were applied, but the outbreak of World War II at the end of 1941 diverted many scientific personnel to other activities until 1946. As a result, many treatments were never properly documented, and many treatments were never properly evaluated or assessed with regard to effectiveness when, and if, the scientists returned after the war. One of the few attempts to draw together documentation of treatments and evaluation of results was done by Valentine (1947) for a number of the areas on the CDRRC. Despite this work, a significant number of treated areas remain undocumented.

Although rangeland remediation treatments range from the water spreading and retention structures of the CCC to more recent rootplowing and seeding activities, the overall aim of the treatments was to stop the advance of shrubs into desert grasslands, reverse the trend of desertification, and reestablish the perennial grass cover. Treatment 'effectiveness' is defined both here and in historical reports (e.g. Valentine, 1947) as the establishment and relative persistence of grass cover in the treated area.

About the same time as the CCC treatments were applied, a new type of observation capability was being applied, namely, remote sensing in the form of aerial photography. An improved camera for producing vertical aerial photographs with minimal distortion was developed by Sherman Fairchild in 1917 for the U.S. military (Thompson & Gruner, 1980). By the early 1930s, the USDA started to systematically photograph agricultural lands in all states. Black and white aerial photographic coverage over parts of the Jornada basin began in 1935. Aerial coverage has continued to the present day in association with nationwide mapping projects or various remote sensing research projects where color infrared photography is flown for comparison with new types of remote sensing instrumentation. Fortunately, these early and subsequent aerial photos have been archived and are available for analysis today. Unfortunately, images from various years are scattered among different archiving facilities across the country. This aerial photographic imagery should assist in documenting treatment extent, pattern, longevity, and resultant effects. Aerial photos are simple to use and interpret, and they are relatively inexpensive to obtain.

Using historical aerial photography (and comparable resolution satellite images) along with little known archival file information, the objectives of this study were to examine and evaluate the rangeland treatments and manipulations (sometimes conducted over large areas) that were made, starting in the 1930s, on the seemingly undisturbed landscapes of arid southern New Mexico. By learning more about long-term impacts and effectiveness of different treatments, we hope to improve the planning of current-day approaches to rehabilitation of desert ecosystems.

Methods

For use in identification of the rangeland treatments, basic air photo interpretation was employed and variations in key characteristics—shape, size, pattern, tone, and location—were used to compare effectiveness and temporal duration. Medium-scale aerial photography as used in this study (1:6000 to about 1:40,000 scale) has been used previously in rangeland studies. This kind of aerial photography has been found to be applicable to rangelands for detailed vegetation mapping, assessment of rodent activities, delineation of erosion features, condition and trend assessment, planning within allotments, and change detection (Carneggie *et al.*, 1983). The addition of color infrared photography can be of assistance in extending the applications to habitat assessment and ecosystem surveys (Tueller, 1982). Generally, the ground resolution of medium-scale aerial photos is 2 m or better.

Aerial photographic databases and mosaic indexes were searched for the Jornada basin, and photographic contact prints and negatives were ordered for each scene of interest over the basin. For reproduction and analysis purposes, both prints and negatives were scanned to digital image files for subsequent computer processing. When compared, the scanned negatives seem to possess more information than scanned prints of the same frame, so they are more useful for analysis. Aerial coverage of the CDRRC was flown in December 1936, just 4 months after some of the major treatments on the CDRRC were applied. Both CDRRC and JER were flown in March 1937 providing more widespread coverage of the area. Both the 1936 and 1937 data were flown by SCS at a scale of 1:31,680. The next coverage in October and December 1947 was provided of the CDRRC at a scale of 1:10,560 as a result of a lower flight altitude. This provided higher resolution views of the treatments and exclosures in place. Although aerial photography was flown over the western part of the CDRRC along the Rio Grande River in 1955, 1960, 1967, and 1969, none of these flights covered rangeland treatments of interest as shown in 1936, 1937, and 1947 air photos.

Flights in February and March 1974, however, covered all the relevant CDRRC and JER areas and were flown at a scale of 1:40,000. Additional flights and photos were available in 1986, 1996, and 1998–2000. The 1996 aerial photos are USGS digital orthophoto products. There was a large gap of coverage over the treatments from 1947 to 1974, and several approaches were attempted to fill that gap with comparable resolution imagery. Additional databases are being searched to find air photo imagery that may not be in the normal archival facilities. Recently, declassified military satellite images from post-1960 have been acquired, although not all treatment areas are covered by the satellite data. For several of the years from the mid-1960s to the mid-1980s, the military satellite images were used to partially fill gaps in the aerial photo coverage. More recent developments in very high-resolution imaging from satellites, such as the 1 m panchromatic imagery from the IKONOS satellite, have produced products comparable with the aerial photos.

The development of information on the rangeland treatments progressed as different photographs were received. Initially, the 1974 and 1986 aerial photos were available, and these images were examined for the entire Jornada Basin. It became evident that a number of anthropogenic features stood out, and scientists at JER and CDRRC were able to explain some treatments in a number of areas; however, many of the treatments remained unexplained. Additional examination of the treatments included numerous field trips to the sites of interest. More documentation was obtained in this manner, followed by perusal of various aerial photo archives. This allowed acquisition of additional aerial photos over sites of interest in order to identify when treatments were applied to the landscape and how long it took for them to disappear. Declassified photos from the military satellites were obtained over some of the treatments when it was evident that aerial photography did not exist for extended periods. Most of the analysis in identifying treatments involved scanning of the aerial photos, creation of digital files, and computer analysis and display.

To assist in reconstructing characteristics of various treatments and their original objectives, several other sources were exploited. Files of unpublished data, internal reports, and published papers at both JER and CDRRC were searched to see if any ground photos, maps, or notes about the treatments existed. Finally, major archives such as the National Agricultural Library and the National Archives were searched to see if any old documentation about the treatments could be found that was not otherwise available.

For most of the rangeland rehabilitation treatments identified with remotely sensed data, there is at least partial documentation regarding objectives, type of treatment, and sometimes an evaluation of treatment effectiveness. Many of the evaluations were performed by Valentine (1947). In the following discussion, plant species are named according to Correll & Johnston (1970), except for grasses, named according to Allred (1993). Those few species not found in Texas are named following Kearney & Pebbles (1964).

Identification of treatments and evaluations of effectiveness

By inspection of aerial photography that started in 1936, we found evidence of several different types of manipulation of vegetation and of the soil surface. These manipulations are comprised of CCC water spreading or retention treatments (including contour terraces, brush water spreaders, and alternating grubbed and ungrubbed strips), revegetation exclosures, undocumented plot studies involving vegetation treatments, rootplow and seeding operations, and water retention dikes. Most of the CCC water spreading and retention treatments appeared to have been applied during the period 1935–1940, mechanical disturbance of the surface and seeding was mostly from 1964 to 1980, and some manipulations of surface drainage to promote grass growth was resumed in the period 1975–1985.

Contour terraces

Pasture 9 on the CDRRC was the site of large rangeland remediation treatments involving water retention and spreading. In this case, 21 contour terraces with a total length of about 24 km covering about 85 ha were constructed by CCC labor in 1935 on a 3–5% slope on the north side of Summerford Mountain extending almost down to the CDRRC Headquarters. The terraces, made with a road grader (Valentine, 1947), were about 2·5 m wide. These terraces were built at 1·8 m contour intervals so that the horizontal distance between contour terraces is about 30·5 m at the top of the slope where it is steeper and about 91·4 m down closer to the Jornada Plain and the CDRRC Headquarters. After construction, some of the terraces were seeded to various native grasses. This seeding or an accumulation of native seeds from upslope source areas was associated with limited concentration of vegetation behind the terraces which was visible in the 1936 aerial photography as shown in Fig. 2 (location A). Adjacent to this area and to the south-east, more closely spaced contour furrows were constructed over about 6·1 ha but at a contour interval of 0·31 m so that the horizontal distance between furrows is only about 7·6 m (see enlargement, Fig. 2, inset C). In the central west part of the contour terraces there is a similar area with even tighter interval contour furrows (see enlargement, Fig. 2, inset B). Figure 3(b) is a line drawing from the files of the NMSU Department of Animal and Range Sciences documenting the pattern compared with the 1947 aerial photo of the same area. In 1937, ponded water broke through many of the terraces. Rock weeps were later installed in the terraces to slowly release the water and prevent future breaches of the terraces (see Fig. 3(c)). Today only the rock weeps remain as evidence of the terrace location. By the time of the 1947 image in Fig. 3(a), the tightly contoured treatments at locations (B) and (C) in Fig. 2 had nearly faded away except for a few remnants.

For the contour terraces in CDRRC pasture 9, data from 11 1-m square quadrats were evaluated. In areas where no seeding occurred, only short-lived species like snakeweed (*Xanthocephalum* spp.) and fluffgrass (*Dasyochloa pulchella*) experienced temporary increases both above and below the terraces. More desirable species like black grama (*Bouteloua eriopoda*) were generally not present to begin with, and very little expansion from areas where it was present was noted in the decade after the

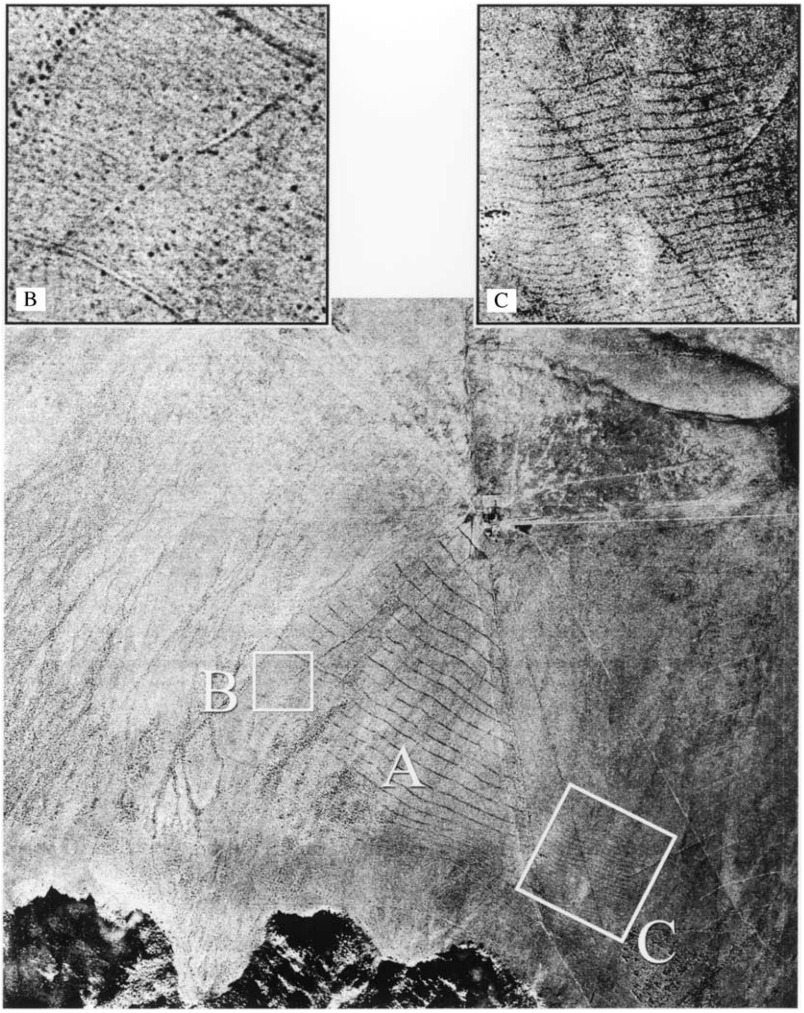

Figure 2. Contour terraces constructed in 1935 in CDRRC pasture 9 as evident in 1936 aerial photography at location (A). More closely spaced contour furrows are located at (B) and (C). Inset (B) is a 5·8 × enlargement, inset (C) is a 2·8 × enlargement.

terraces were constructed (Valentine, 1947). On and beside terraces that were seeded with several grasses, several locations experienced moderate growth but the areal extent of the response was very limited, and most of the plants remaining today are native species represented in the pre-existing vegetation. The overall evaluation by Valentine (1947) was that, in general, little vegetation improvement could be attributed to the terraces.

Brush water spreaders

In the same general area of CDRRC, but in adjacent pasture 8, brush water spreaders were constructed in 1937. The spreaders were made of brush gathered locally and were held down by wire ties at 60–90 cm intervals across the spreader, and the knotted ends of the ties were anchored in the ground with a driving tool (Valentine, 1947).

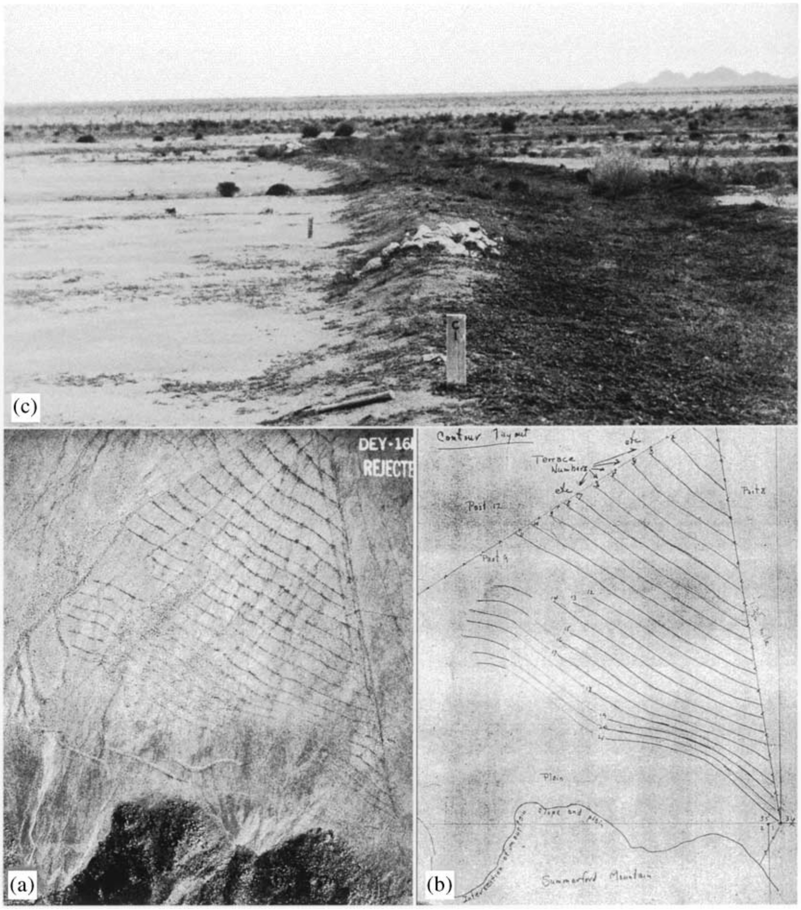

Figure 3. (a) 1947 aerial photo of CDRRC pasture 9 contour terraces on north-facing slope of Doña Ana Mountains. (b) Hand-drawn schematic of contour terraces from NMSU files. (c) Ground view of contour terrace across mountain slope soon after installation (with rock weep to allow water to seep through terrace) (after Knox *et al.*, 1951; credit New Mexico State University, College of Agriculture Photo Archives).

The spreaders received water from small rock dams constructed across arroyos draining mountain slopes and carried the water along the contour until the water infiltrated or passed through the spreader. Figure 4(b) shows how the spreaders appeared soon after placement on the ground. Figure 4(a) shows the appearance of the brush spreaders in CDRRC pasture 8 from the 1947 aerial photography. Because there was no long-term visible vegetation growth associated with the brush spreaders, certain key features had mostly faded from the aerial imagery by sometime after 1972. Isolated remnants of the brush spreaders, however, could still be identified in the military satellite images taken in the 1980s and aerial photos of the 1990s. Their aerial identification lifetime as a fully visible treatment was about 35 years. Five pairs of quadrats were established in areas above and below the brush spreaders. Aside from the fact that seed of desirable grasses would lodge and germinate in very limited areas immediately adjacent to and within the brush spreaders (microsites), little areal improvement was noted. 'In general it is impossible to identify any area above or below the spreaders that have been benefitted by them' (Valentine, 1947). This conclusion is also true today. Again, no maintenance was performed on the brush

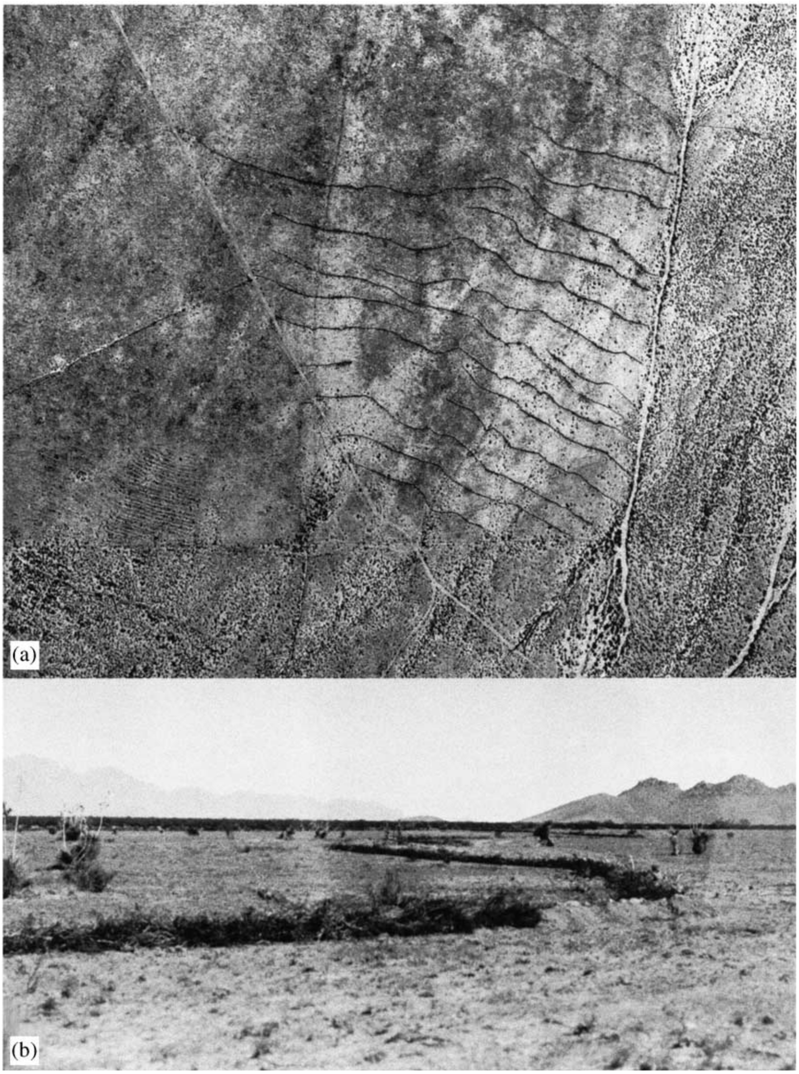

Figure 4. (a) 1947 aerial photo over CDRRC pasture 8 showing brush spreaders installed in 1937. (b) Ground view of brush water spreader on mountain slope with rock check dam soon after installation (after Knox *et al.*, 1951; credit New Mexico State University, College of Agriculture Photo Archives).

spreaders or the small rock dams used to divert water to the spreaders. Without maintenance, breaks in the small dams severely reduced the amount of water available to the spreaders, and the brush in the spreaders was also quickly removed by wind and water so that the effect on revegetation would be minimal over time. The last remaining evidence of the brush spreaders on the ground is the still firmly anchored wire ties every 60–90 cm along the contours.

Grubbed strips

Although most rehabilitation treatments installed during the 1930s were along topographic contours, one of the more impressive and somewhat mysterious treatments was not contour referenced. In July–August 1936, with the assistance of the Soil Conservation Service and the Civilian Conservation Corps (CCC), creosote (*Larrea tridentata*) and tarbush (*Flourensia cernua*) shrubs were removed at the root level (grubbed) from 89 ha of rangeland in pasture 10 of the CDRRC. Honey mesquite (*Prosopis glandulosa*) and yucca (*Yucca* spp.) plants were left undisturbed. Although not much different in total area from the contour terraces in pasture 9, the geometry of the treatments was striking. The grubbing was done in straight linear strips 30·5 m wide and 3·1 km long. There were five grubbed strips separated by 15·25 m wide ungrubbed strips. Brush from the grubbed strips was piled at the west edge of the ungrubbed strips, probably to slow the flow of water off the grubbed strips. According to file records, on October 10, 1939, creosote and tarbush were again removed from the middle 30·5 m grubbed strip. The grubbed strip to the east of the middle strip was also grubbed again on October 10, 1939, but this time all shrubs—including mesquite and yucca—were removed. It is stated in reports (Agricultural Experiment Station, 1940) that the regrubbed areas would be kept free of brush whenever necessary. However, the 1939 regrubbing was apparently the last shrub removal treatment the strips received, probably because of the occurrence of World War II and the loss of the labor force on the experimental ranges. It was not clear from records whether this retreatment of two strips was conducted just in a limited portion of the study area or if the regrubbing was carried out over the entire length of the strips (3·1 km). Close examination of 1947 aerial photos, however, shows that these 1939 treatments were confined to a small portion of the strips.

Two aspects of this treatment are unusual. First, the treatment, which extended to placement of brush piles, was performed in a straight line and not on a topographic contour as nearly all other similar brush-related treatments were in this region. Second, the area of the treatments is unusually large and very visible when flying over the region.

From aerial photographs taken by the Soil Conservation Service in December 1936 the pattern of treatment approximately 4 months after grubbing is clearly illustrated in Fig. 5(a). In addition to the five aforementioned grubbed strips, a sixth grubbed strip in the north-east sector was started but never completed. This sixth strip runs for about 235 m. It is not clear whether it was intended to run the whole length of the pattern, or if it had another purpose. It is never mentioned in any reports still available. It should be noted that some small square exclosures were constructed adjacent to the west side of the pattern which remain undocumented. Current day inspection seems to indicate that at least a part of these exclosures was cleared of shrubs and used to plant four-wing desert saltbush (*Atriplex canescens*), black grama, and other seeded species.

The long parallel strips in pasture 10 are visible in every image we have which covers that area from 1936 up until the present day. Figure 5(a–e) shows a temporal sequence from 1936 to 1998, and it is evident that the strips are still visible from above although it is much more difficult to detect them on the ground. However, when a temporal sequence of aerial photos for the contour terraces in pasture 9 was examined, it is clear that these features had almost entirely faded away in 40 years. There are perhaps two reasons for the persistent visibility over time of the grubbed strips. First, a much larger contiguous area was treated (30·5 m wide strips) compared with the contour terraces (about 5·0 m wide terraces and borrow pits combined). Therefore, a stronger contrast with the surrounding undisturbed desert vegetation and soil complex is provided in the grubbed area which has remained fully visible for a longer period (at least 65 years). Second, the pattern of disturbance is much more geometrical for the grubbed strips, and they stand out more than do the more natural patterns of contour structures. The blending of the treated area with undisturbed adjacent vegetation takes place more rapidly in the contour treatments. Despite the fact that the grubbed

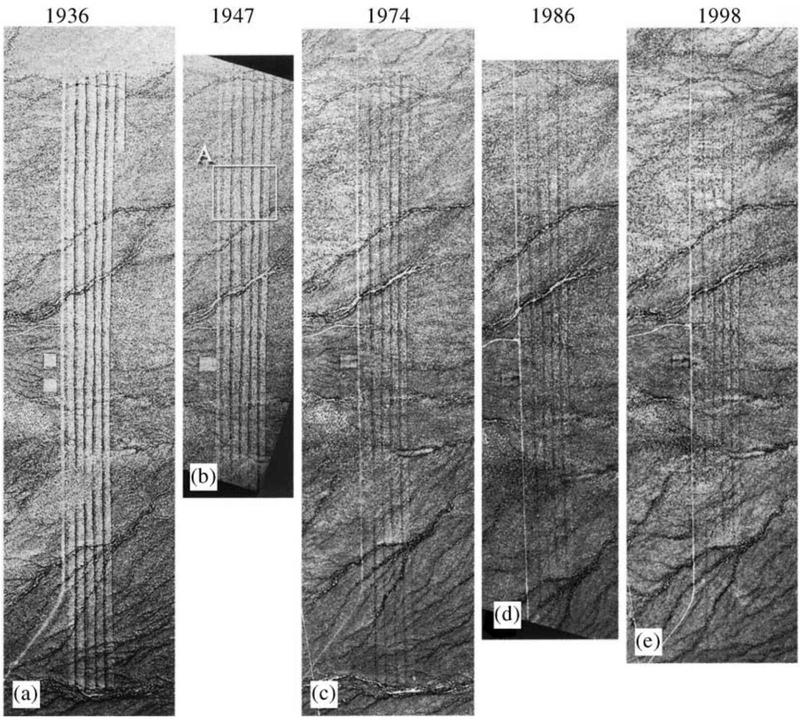

Figure 5. Temporal sequence of (a) 1936, (b) 1947, (c) 1974, (d) 1986, and (e) 1998 aerial photos of alternating grubbed and ungrubbed straight line strips in CDRRC pasture 10. At the west end of the ungrubbed strips, brush from the grubbed strips was piled. White square A in 5(b) represents the image area in Fig. 6(a).

strips are the single largest treated area in the Jornada basin, Valentine (1947) did not include an overall evaluation of the strip treatments in his report.

Revegetation exclosures

In association with treatments like the parallel strips, various exclosures were set up to study 'the revegetation of south-western ranges by controlled grazing, utilization of runoff water, and reseeding' (Agricultural Experiment Station, 1936). As an example, in the northern part of the strip pattern where the 1939 regrubbing took place, a 2·43 ha rabbit-proof exclosure (#17 in the CDRRC numbering scheme) was established in 1939 to study the effects of rabbit grazing on vegetation composition in this treated area. In the exclosure, 32 subplots in squares of 7·62 m on a side were set up in the middle strip regrubbed of creosote and tarbush in 1939, 32 more subplots in the strip just east of the middle strip and regrubbed of all shrubs in 1939, and a final 32 in an ungrubbed strip. A similar number of subplots located in the same way were established south of the rabbit-proof exclosure (see Fig. 6(b) from NMSU Department of Animal and Range Sciences files). Figure 6(a) (which appears as square A in the 1947 coverage in Fig. 5) shows this same area as it appeared on 1947 aerial photography; a careful inspection reveals the fence boundary of Exclosure 17 which is highlighted with white arrows. Because this entire area is in CDRRC pasture 10, which was ungrazed by cattle, all subplots were protected from the effects of cattle grazing.

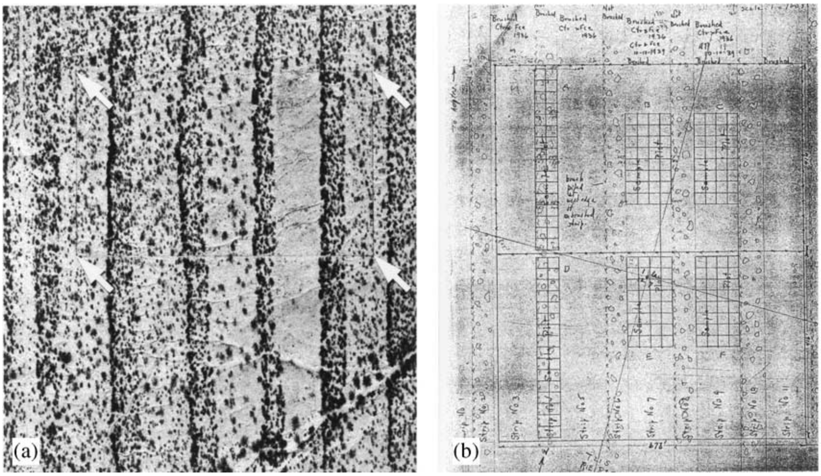

Figure 6. (a) 1947 aerial photo of CDRRC exclosure 17 (as defined by white corner arrows) in the parallel strips. (b) Hand drawing of exclosure 17 experimental design from NMSU files.

Some conclusions specific to Exclosure 17 were made. Exclusion of rabbits from the fully grubbed strip resulted in a noticeable growth response in the first year (1940) of dropseed grass (*Sporobolus* spp.) and fluffgrass compared with outside the exclosure (Agricultural Experiment Station, 1940). Much higher than normal rainfall in 1941 allowed continued improvement inside the exclosure with impressive growth of six different grasses and 15 different forbs compared with outside the exclosure (Agricultural Experiment Station, 1941). Further evaluations were not made, and the plots and strips were not maintained, contrary to indications in 1940 that they would be (Agricultural Experiment Station, 1940). The area of the grubbed strips today seems to have returned to shrub domination with very little grass growth. The fencing for Exclosure 17 has broken down and is visible only in a few spots where it has been protected by shrubs.

To the north of the strips and of Exclosure 17, a second exclosure (#18), also in pasture 10, was set up to determine the joint effects of cattle and rodents on various types of land terracing, the singular effect of rodents on the contour terraces, and the ability of the contours to increase natural forage production with the complete exclusion of cattle and rodents (Agricultural Experiment Station, 1940). Exclosure 18 comprises five contiguous plots in low-condition grassland fenced to exclude rodents and five similar adjacent plots not protected from rodents. The fence for Exclosure 18, which was constructed in 1939, is visible on the 1947 air photo and encloses 5 ha (Fig. 7). The unfenced treatment plots adjacent to Exclosure 18 are also visible in Fig. 7. The two sets of five plots were meant to assess rodent effects on vegetation associated with various contouring treatments and include ridge contours (9–14 m spacing), large ripper furrows (3–4 m spacing), double furrows (8–11 m spacing), a control, and small single furrows (l–2 m spacing) in order from south to north (Valentine, 1947). It is interesting to note that in addition to these ten plots, inspection of the aerial photos reveals many similar contour treatments scattered over this entire area of CDRRC, most of which are undocumented.

There is very little evidence today that Exclosure 18 ever existed other than some very regular rows of wooden stakes delineating some plot boundaries. All fencing has been removed from the area. Valentine (1947) pointed out that soil moisture measurements in and around Exclosure 18 revealed that none of the contour treatments provided any increase in soil moisture. The lack of response in perennial

Figure 7. 1947 aerial photo of CDRRC exclosure 18. Five plots are inside the exclosure as delineated by the dark fence line (and protected from rodent effects) and five more identical plots are outside the fence to the east (and not protected from rodent effects).

grass growth in this area was probably associated with this lack of moisture enhancement. Valentine (1947) speculated that grass growth at this site, unlike other sites where exclusion of rodents and rabbits resulted in an improvement in vegetation growth, was more constrained by the poor water-holding capacity of the soil (coarse sandy loam over coarse sand) which most likely prevented the contouring strategies from being effective in producing increased grass growth.

Undocumented plots

An area on JER pasture 6, that was first noticed when the aerial photography was examined, remains very much a mystery. This pattern of plots, which still has wooden stakes marking the plot corners (dimensions of $7{\cdot}5 \times 30\,m^2$), remains quite visible

Figure 8. 1974 aerial photo of JER pasture 6 south and west of Doña Ana Revegetation and Rain Gauge Enclosure where a rectangular plot pattern of unknown treatments exists.

because it covers a large, remote area (26·5 ha) south and west of the Doña Ana Revegetation and Rain Gauge Enclosure. About one-half of these plots actually are in the North Plot of the larger Doña Ana Exclosure (formerly known as the Moisture Conservation Exclosure). Today, some of these undocumented plots remain nearly free of any vegetation, whereas others are covered by a sparse vegetation, and others have a normal shrub cover consisting mostly of creosote. No one interviewed or taken to see these plots in 2000 was previously aware of their existence. No reference to these plots was found in existing reports or files. They are not present on the 1937 aerial photography and were first noticed on the 1974 aerial photography (see Fig. 8). Because of the extent of these plots and the labor required to put them in and manipulate the vegetation, it is likely that they were established in the late 1930s or early 1940s before the CCC left the region. It is very unusual that no reference or documentation could be found considering the effort that was required to work in this remote region. Uncovering additional details about these plots would be valuable for retrospective studies. Initially, it appeared that there was a large gap in aerial photo coverage over this portion of the Jornada basin between 1937 and 1974. Recently, military and private company aerial photos from 1940s to 1950s were located and ordered for this region. When received, they should help determine at least when the plots were installed.

Rootplow–seeding patterns

In the period after World War II, individual rangeland remediation treatments did not cover areas as large as in the 1930s, but these more recent treatments were better documented. Numerous implements were designed to exploit the ever increasing power of agricultural and civil engineering machinery to remove shrubs, prepare seedbeds, create small pits where water could accumulate, and plant seeds. The arid land seeder, a machine which accomplished all these operations in a single pass, was developed at JER in 1967 and tested during the 1960s and 1970s (Herbel *et al.*, 1973; Abernathy & Herbel, 1973). Figure 9 shows an aerial photo of the pattern of a precursor to the arid land seeder machine in JER pasture 6 in a tarbush area taken in 1974. In the period 1964–1966, a road grader and accompanying seeding machine, as seen in Fig. 10, were used in the area shown in Fig. 9 in an attempt to replace tarbush with grass and to perfect techniques using heavy machinery. In some tests, pits were made by the end of the road grader blade and then seeded. This type of pit pattern is likely seen in the third strip from the west and the eastern-most strip in Fig. 9. To the north-east of the major pattern, several additional patterns are evident indicating that

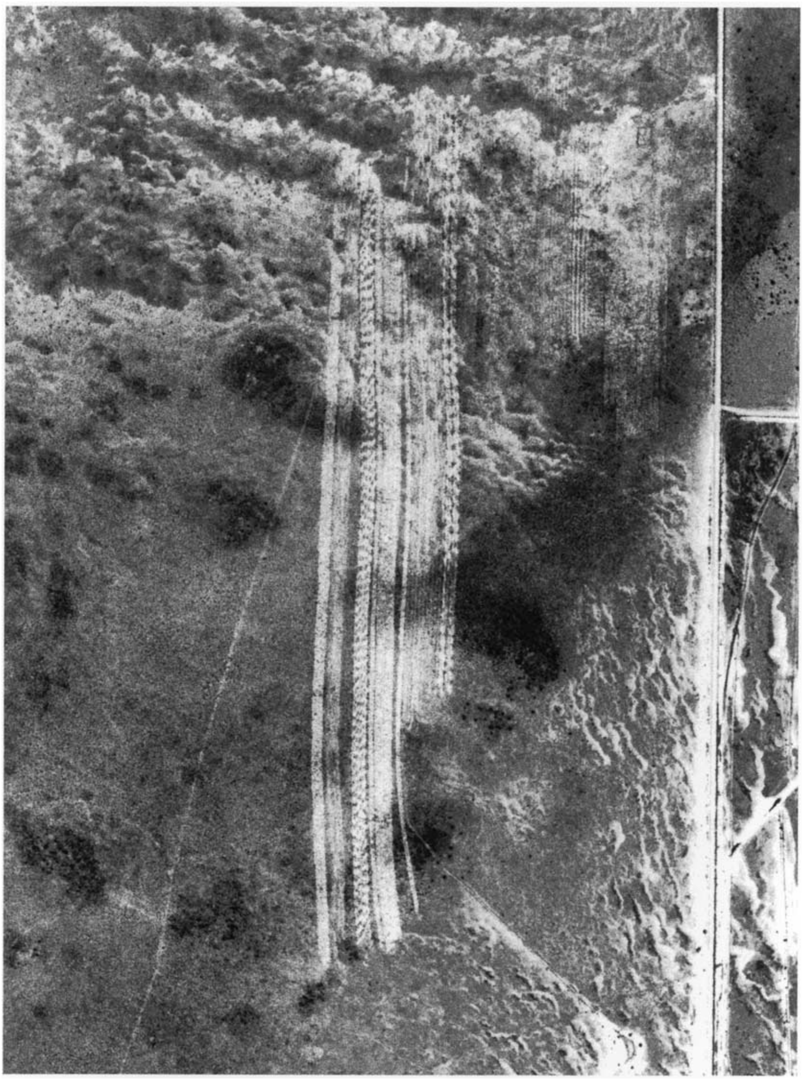

Figure 9. 1974 aerial photo of JER pasture 6 east side showing surface patterns left by road grader and seeding machines.

Figure 10. Road grader and grass seeding equipment operating in tarbush area of JER pasture 6 in 1964.

seeding methods which produced less surface disturbance were also tested. Treatments with the final version of the arid land seeder display patterns much more muted or homogeneous than those in Fig. 9. All these treatments, however, resulted in relatively high levels of soil surface disturbance which increased erosion susceptibility (Herrick *et al.*, 1997). They also required significant energy inputs and the availability and maintenance of expensive machinery.

Use of the arid land seeder that was eventually developed was not confined to the JER, and results in 23 2-ha plots across southern New Mexico were evaluated. Approximately 50% of the seedings were considered to be successful 6 years after seeding (Herbel *et al.*, 1973) based on six levels of subjective assessments at each of the 23 plots. Drought was cited as the primary reason for failure, combined with highly erosive sites or ones subject to formation of hard surface crusts (Herbel *et al.*, 1973). Because of drought and unfavorable soil conditions at Jornada, all of the seven JER plots treated with the rootplow–seeder were unsuccessful in causing grass regrowth.

Water retention dikes

In 1981 at the south end of JER pasture 6, 12 slightly crescent-shaped dikes designed to impound about 15 cm of water before any excess overflowed around the ends of the dikes were built (Tromble, 1981). The dikes are about 30 cm high and about 60 m long. The gravelly-loam soils of the impoundment areas were rootplowed to eradicate shrubs and drill-seeded with sudangrass (*Sorghum bicolor* spp. *drummondii*), blue panicgrass (*Panicum antidotale*), alkali sacaton (*Sporobolus airoides*), and Lehman lovegrass (*Eragrostis lehmanniana*) according to JER annual progress reports. Seeded species have not survived, but the more favorable environment created by the dikes has led to relatively lush growth of native species, and the dike area in recent imagery has a much lower reflectance (see Fig. 11(a)) indicating significant vegetation growth covering the normally highly reflective soils as shown in the ground view in Fig. 11(b). This reinvasion by native species has also occurred on other areas where

Figure 11. (a) 1986 aerial photo of JER pasture 6 west side showing 12 dikes constructed to retain surface runoff for infiltration and combined with seeding of various grasses (white arrows point to abundant vegetation growth areas upslope from dikes. (b) Ground view of grass and associated vegetation growth upslope from dikes in (a) taken in 1999.

impoundment dikes were built. For example, five concentric 7·5 cm high dikes were established on a fine-textured soil in 1975 in an area with virtually no perennial plant cover. During the next 4 years, various treatments were applied including disc plowing, seeding and, in 1979, the application of municipal biosolids. The experiment was abandoned in 1980 because of the lack of plant establishment and the costs of maintaining the dikes. By 1984, there were still very few plants growing between the dikes. Significant recovery of native species was recorded, however, when the site was resurveyed in 1997 (Walton *et al.*, 2001). The patterns are now clearly visible from aerial photographs. Like the other dikes, most of the plants established on the site were native species which colonized from the pre-existing seed bank or the surrounding area. In arid regions, significant rainfall events and subsequent runoff are not frequent, so it may be necessary to maintain the treatments for longer periods than would be necessary in humid regions in order to encounter the precipitation events that would activate the treatments or support plant response.

Fenceline contrasts

Fenceline contrasts are common features in aerial or satellite photography where treatments have been instituted or where different land ownerships or management practices meet. The reasons for the strong contrasts across fences include grazing restrictions (a passive treatment), different stocking levels or patterns, distance from water sources, and differing treatments as well as natural soil, water and vegetation discontinuities that might parallel fence lines. Improved resolution images from satellites, like the recently launched IKONOS, can show fenceline contrasts in a fashion comparable with aerial photography. An example of fenceline contrasts is shown near the center of Fig. 12 which is 1–2 m resolution IKONOS satellite imagery located over the boundary intersections of the CDRRC, JER, and Bureau of Land Management (BLM) lands (to the northwest). The sharpest fenceline contrast is between the northern edge of CDRRC pasture 3N and the BLM lands to the north at location A. In contrast to CDRRC and JER lands shown in Fig. 12, where herbicides have been applied at different times in the past to control the shrubs, the BLM land to the north has never been herbicided. The BLM land has been heavily grazed for long periods, and shrubs dominate the vegetation cover as opposed to portions of CDRRC and JER where black grama remains. A ground view of the fenceline contrasts between CDRRC and BLM at location A is shown in Fig. 13. The fenceline contrast at location B in Fig. 12 is a black grama exclosure established in the 1950s that was subjected to different grazing intensities until the mid-1960s and then eventually excluded from grazing entirely. Today the black grama in the exclosure is in very good condition.

Temporal visibility of treatments using remote sensing

Monitoring the length of time that the rangeland treatments were visible with remote sensing data was complicated by the fact that aerial photography was not always available over all the treatments. Declassified military satellite images from 1968, 1972, and 1983 were used to increase the number of photos over the treatment areas. Not all of the treatments in this study were covered by military satellite images because of the restricted areal coverage available. The appearance of rangeland treatments from 1936 to 1996 could only be assessed for the contour terraces (Fig. 2), the brush spreaders (Fig. 4), the grubbed strips (Fig. 5), and Exclosure 18 (Fig. 7), all of which are on the CDRRC.

Six years of photo coverage were used to observe the particular treatments as shown in Table 1. The first year that the treatment was observed (1936 or 1947) was used as a baseline against which to compare the appearance in subsequent years. When some key features in each treatment had disappeared, the treatments were deemed only partly visible. It can be seen from Table 1 that the large contour terraces (Fig. 2(A)) persisted for at least 37 years before their identification became problematic. Parts of the terraces could still be discerned in 1996. The tightly spaced contours in Fig. 2B, C were difficult to identify 12 years after installation and faded away entirely sometime between 1947 and 1968. The brush spreaders were easily observed for 35 years and became difficult to see after 1972, although traces of the spreaders are still visible today. Exclosure 18 was only visible in certain parts, probably because fencing was removed in the period 1947–1983 combined with natural degradation of the enclosed contour structures. After 1983, Exclosure 18 could no longer be identified, and no

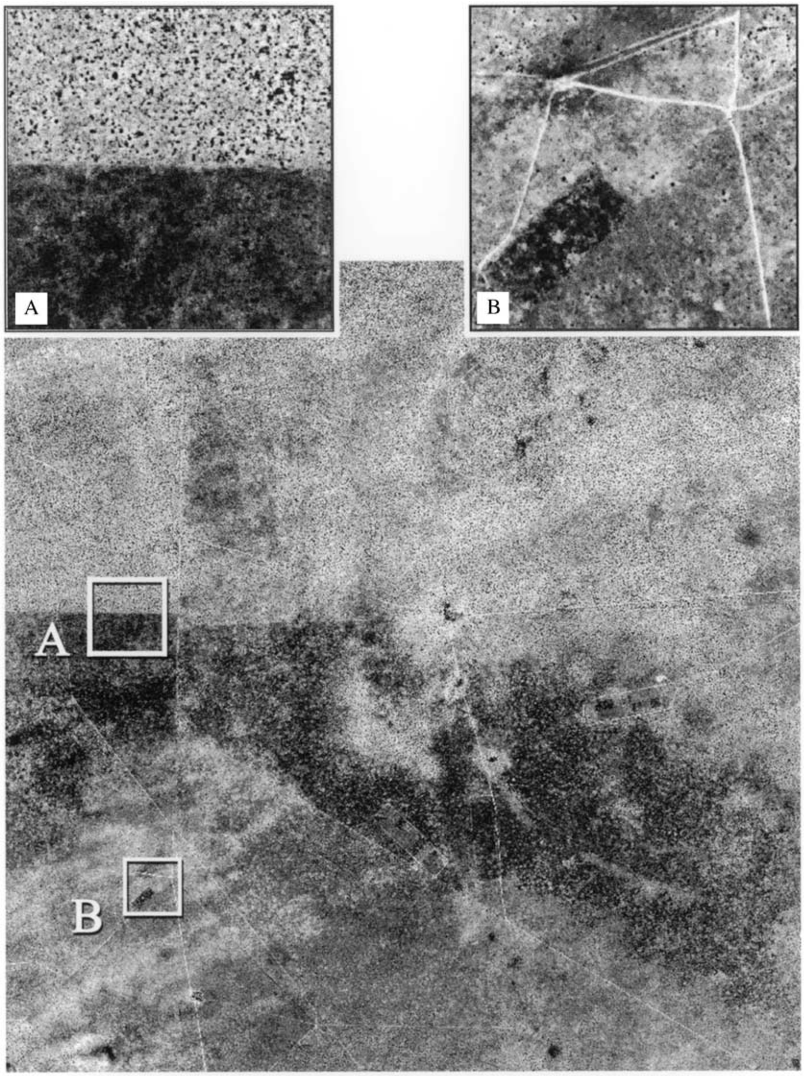

Figure 12. IKONOS panchromatic image over CDRRC, JER, and BLM lands taken on July 20, 2000. Location (A) is the fenceline contrast between CDRRC pasture 3N and BLM lands. Location (B) is a black grama exclosure. Inset (A) is a 4·7 × enlargement and inset (B) is a 6·4 × enlargement.

fencing remains on the ground. Only the 3·1 km long grubbed strips remained highly visible during the entire period of record, thus indicating that, from an aerial perspective, their lifetime exceeds 60 years.

Discussion

Guidance for location of new treatments or experiments

Because of extensive existing aerial photography and satellite images, the remote sensing data base resource should be exploited whenever remediation or restoration

Figure 13. Ground view of the fenceline contrast shown in Fig. 12, inset (A) with BLM land on the left and CDRRC land on the right.

Table 1. *Longevity of remediation treatments in aerial and satellite photos in the Jornada basin*

Treatment	Year treatment constructed	Year of observation					
		1936	1947	1968	1972	1983	1996
Contour terraces (Fig. 2(A))	1935	y	y	y	y	p	p
Contour terraces (Fig. 2(B))	1935	y	p	n	n	n	n
Contour terraces (Fig. 2(C))	1935	y	p	n	n	n	n
Brush spreader (Fig. 4(a))	1937	—	y	y	y	p	p
Grubbed strips (Fig. 5)	1036	y	y	y	y	y	y
Exclosure 18 (Fig. 7)	1939	—	y	p	p	p	n

Observation key: y—treatment observed with all original features visible, p—partially visible with some key features observed, n—treatment no longer visible.

activities are proposed. It is an excellent way to become familiar with the study area of interest. This is especially true for students, scientists, or ranch managers who may be new to a particular location. The remote sensing data can be used to build up knowledge of the type of treatments already applied in the area and their resulting effects. Where natural or artificial boundaries exist, remote sensing data can be used to determine where to locate supplemental ground measurements to aid in the design of new experiments.

Because the historical manipulations are difficult to detect on the ground, new treatments and studies may accidentally be located in previously affected areas. For example, long-term plots were established in 1989 by the Jornada Basin Long-Term Ecological Research (LTER) program to monitor above-ground plant composition and net primary productivity. Two of the plots located in creosote bush ecosystems fall in or near the parallel grubbed strips described previously. In portions of these plots, then, plant density and size may be smaller than in surrounding untreated areas. Assumptions that the plots reflect maximum plant biomass for undisturbed sites would therefore be in error. An accurate understanding of how plant productivity and ecosystem structure are related to historic disturbance depends on being able to reconstruct plot histories; the current study demonstrates the value of archival information in documenting historical treatments no longer conspicuous on the ground.

Effectiveness at landscape scales

Experimental manipulations of rangeland on the scale of small plots have for the most part been ineffective because there was no way to prevent processes occurring across landscape units as a whole from overwhelming the treatments. Examples of these processes are rainfall-runoff generation, soil erosion, fluxes of water, nutrients, and seeds down the topographic slope, and drought. In addition to the fact that the treatments were not performed over large enough or contiguous areas, there were other reasons contributing to failure of the experimental manipulations. These reasons include: (a) maintenance of treatments not included as a continuing activity in the experiment design; (b) evaluation of success of some treatments was over periods shorter than the return period of significant meteorological events that would interact positively with the treatment; (c) treatments were usually for a single purpose and did not include complementary or multi-purpose treatments to maximize effects; and (d) location of treatments were for the most part not in favorable sites that would respond in a very positive way to the treatment (so-called 'trigger sites').

To have an effect at the landscape scale, treatments have to be conducted at a scale comparable to processes active across the landscape. As an example, Exclosure 18 on the CDRRC, with various types of contour furrowing, was relatively small (5 ha), so treatments were compromised in a relatively short period of time as a result of runoff and erosion processes originating outside the treatment area. Even treatments over relatively large areas did not have a high chance of success because the treatments were not maintained over time. Large features such as the linear grubbed (shrub-free) strips that run for 3·1 km across contours on the south-eastern part of the College Ranch have nearly faded away due to a nearly constant flux of water, nutrients, and seeds transported down slope from the mountains allowing shrub reestablishment. Several arroyos cut through the strips in their course from the slopes of Summerford Mountain down to the Jornada plain. The large areal extent of these treatments has allowed them to be visible for more than 60 years, but it is apparent that they will soon vanish from the landscape as a result of the lack of provision for maintaining the shrub-free strips. By viewing the changing appearance of the various remediation treatments from the ground and from aerial photos, it is apparent that periodic maintenance of the treatments is necessary even in arid and semi-arid regions. In most cases, treatments would need to be updated or maintained at 10-yr intervals or shorter. Although complete shrub reinfestation on the JER is estimated to take about 25 years (for tarbush) (New Mexico College of A and M.A. and Southwestern Forest and Range Experiment Station, 1946), maintenance should be conducted much more frequently because grubbing is more effective, easier, and less expensive when shrubs are young (Agricultural Experiment Station, 1949).

Many treatments are part of experiments that are only evaluated for a limited time period. In most cases, this time period is much shorter than the return period of significant hydrometeorological events (e.g. 50 yr or 100 yr flood) that are needed to activate the treatment in arid regions. On the other hand, extreme climate events such as drought can persist for very long periods so that vegetation associated with effective treatments is eventually eliminated. In the area of the 12 dikes constructed in JER pasture 6, brush was controlled by rootplowing, four species of grass were seeded with a drill prior to the summer rainy season, and water retained behind the dikes was available for vegetation growth. Possibly because of the three-pronged attack, this site has allowed reestablishment of native vegetation cover which can be seen quite easily in aerial photo images from 1986 and in the 1990s. Treatments such as these water retention dikes may be successful because they are located in areas favorable for change. Remote sensing would be effective in identifying areas with a high potential for change, or trigger sites, because it can be used to locate ecotones and areas of resource accumulation. It may be easier to cause change by locating a remediation treatment in a trigger site zone. Other types of trigger sites may encourage improvement in larger areas by natural spread from the treated portion. Thus, the trigger site concept can refer both to how easy it is to trigger changes, and to the possibility that a change in one part of the landscape may trigger changes in surrounding areas. This trigger site concept was presented in 1939 in internal Jornada reports (Southwestern Forest and Range Experiment Station, 1939). No definitive confirmation of this 'trigger site' theory has yet been established, and it is an important area for future research.

Conclusions

Despite the fact that there are vast areas of public and private lands in the arid southwest U.S. of seemingly undisturbed landscapes, there is a complex array of rangeland remediation treatments present that in most cases is not easily detectable from the ground. These manipulated areas extend back to the early part of the 20th century and all the way up to the year 2000. Usually, the older manipulations do not have significant documentation of location, type of treatment, scientific objectives, or an evaluation of effectiveness. Fortunately, there are ways to reconstruct the history of treatments that involve file searches of archival information and exploitation of the ever-growing remote sensing database.

One of the most simple kinds of remote sensing data, namely, aerial photography, can be the most valuable. Not only can the air photos provide a historical, temporal, and areal perspective of rangeland remediation treatments, but techniques used in analysis are simple and easily transferred to users. For the Jornada basin, aerial photo coverage was available and acquired for the years 1936,1937,1947,1974,1986, and 1996–1999. For specific study areas, comparable declassified military satellite imagery was obtained for the 1960s, 1970s, and 1980s. High-resolution multi-spectral data from the IKONOS satellite with resolutions comparable with the aerial photos were obtained for July 2000.

Using the aerial photos, it was possible to identify contour terraces and associated contour structures (with furrow spacing as small as 1–2 m), brush water spreaders, long parallel strips with different grubbing patterns, revegetation exclosures of various types, mechanical rootplow and seeding patterns, water retention dikes, sharp fenceline contrasts, and a mysterious network of plots with, so far, unspecified treatments. When the air photo record was supplemented with declassified military photos, it was possible to delineate the length of time that the various plots were visible with a recognizable pattern from an aerial perspective. For the treatments monitored over time, the 3·1 km long grubbed strips were the most persistent and are still easily visible today even in their 65th year. The brush spreaders and the large contour terraces lasted about 35 years before their identification became difficult. Tightly spaced contours faded away much faster than the large contour terraces.

Based on existing literature and air photo evaluations, no positive vegetation response, such as expansion of native grasses, could be detected for the contour treatments, brush water spreaders, and grubbed strips. The treatments that seemed to have a definite positive response visible from aerial photography were water retention dikes and certain exclosures.

By identifying the location and type of historical treatments, aerial photography can be used to provide a template over rangeland areas. This template can be used effectively to decide the location of new rangeland treatments or other forms of experimental studies so as to avoid contamination by past treatments. Additionally, the template can also be used to locate transects and quadrats for current day measurements to evaluate the effects of the past rehabilitation attempts and evaluate the potential of future treatments. Keeping track of the cumulative manipulations would be facilitated by combining digitized aerial photography with a Geographic Information System.

It appears from both aerial photos and existing conventional documentation that experimental manipulation of rangelands at the small plot scale has generally been ineffective on the landscape unit scale. The reasons for this ineffectiveness include treated areas not large enough, regular treatment maintenance not provided, evaluation periods sometimes too short, multi-purpose treatments not usually performed, and treatments located in unfavorable sites to trigger a positive vegetation response.

There are several aerial photo archives that can be searched to determine what data are available for specific arid rangeland areas in the United States. These data are usually available for ordering at reasonable prices. These facilities include the Aerial Photography Field Office, Farm Service Agency, USDA (www.apfo.usda.gov/orderingimagery.html), the National Archives (www.nara.gov/research/ordering/mapordr.html), the US. Geological Survey (edcsnsl7.cr.usgs.gov/EarthExplorer/), and the Fairchild Aerial Photography Collection at Whittier College (www.whittier.edu/fairchild/home.html).

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