Research in the Jornada Basin of Southern New Mexico: A Field Tour

Kris Havstad
Reldon Beck

Abstract—During the Ninth Wildland Shrub Symposium in Las Cruces, New Mexico, May 22-24, 1995, a field trip took participants to the southern end of the Jornada del Muerto Basin, an area of intensive research in desert ecology and rangeland management throughout the 20th century. The tour highlighted some of the historical studies in grazing management as well as current interdisciplinary research projects involving dozens of scientists from many institutions. Cooperating institutions and agencies include the USDA Agricultural Research Service, New Mexico State University, the National Science Foundation and the Environmental Protection Agency.

History

The Jornada Basin in southcentral New Mexico is often called the Jornada del Muerto (journey of the dead). It lies to the east of the Rio Grande on a plain 100 m above the river. The San Andres Mountains border it on the east. The plain varies in width from 8 - 50 km and is about 150 km long. The basin is primarily closed with limited external drainage on the west edge.

One can still see remnants of the Camino Real which resulted from Spanish traders, soldiers, and others traveling in the 1500's between Chihuahua City, Mexico, and Santa Fe. The trail was used into the early 1900's. The plain received its "del Muerto" label because of the many hazards along this segment of the trail. The rough terrain along the Rio Grande forced the development of this route across the sandy basin. The 140 km stretch in the Jornada Basin was typically dry and generally required four to five days for a caravan to traverse.

Livestock were introduced into the region during the early part of the 17th century, but grazing was generally limited to the Rio Grande valley and adjacent slopes because of lack of surface water in the surrounding basin. Some water could be found in springs and seeps in the mountains, but supplies were ephemeral. In the late 1800's the first permanent well was dug in the basin which allowed a continuous source of water for livestock. With development of surface water large livestock operations were established. One of the largest was the Detroit and Rio Grande Livestock Company. Around the turn of the century, Mr. Charles T. Turney acquired many of the water rights from the Detroit Company and other ranchers in the area. It was from the land holdings associated with these water rights and the surrounding public domain that eventually the USDA Jornada Experimental Range and the New Mexico State University's Chihuahuan Desert Rangeland Research Center were established.

The USDA's Jornada Experimental Range (JER) was established in 1912 by Presidential Executive Order from Turney's lands (and water rights) and public domain withdrawal. The current holdings are only slightly less than the original 78,297 ha withdrawn at establishment. Elevations range from 1,275 m on the plains to 3,790 m in the San Andres Mountains.

The University's Center was established in 1927 by the U.S. Congress giving public lands to the State of New Mexico for research, educational and demonstrative purposes. Today, the total area within the Center is over 25,500 ha. It is bordered on the west by the Rio Grande at an elevation of 1,220 m and includes Summerford Mountain on the eastern side with an elevation of 1,780 m. The eastern border is shared with the Jornada Experimental Range. On the experimental ranges, annual rainfall is near 24 cm with 53% falling in July through September. Soils vary from unconsolidated alluvium in the mountains, to sandy loams in the plains, to clay in the playas and along the river. Seven different vegetation types are present.

General Features

Vegetation

The Jornada plain is usually classified as semidesert grassland, an ecosystem which covers about 10.5 million ha in southeastern Arizona, southern New Mexico, western Texas, and northern Mexico. The area is within the northern portion of the Chihuahuan Desert (fig. 1). Although called "grassland," the region contains a complex of vegetation types ranging from nearly pure stands of grass, through savanna types with grass interspersed by shrubs or trees, to nearly pure stands of shrubs. The mountains, plains, and drainageways provide a great variety of habitats for plants, and the flora is rich in species. Some 545 species of higher plants have been collected in the area.

The major grass species on sandy soils are black grama (*Bouteloua eriopoda*), mesa dropseed (*Sporobolus flexuosus*), and red threeawn (*Aristida purpurea* var. *longiseta*). Shrubs or shrub-like plants on sandy soils include honey mesquite

---

In: Barrow, Jerry R.; McArthur, E. Durant; Sosebee, Ronald E.; Tausch, Robin J., comps. 1996. Proceedings: shrubland ecosystem dynamics in a changing environment; 1995 May 23-25; Las Cruces, NM. Gen. Tech. Rep. INT-GTR-338. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station.

Kris Havstad is Supervisory Range Scientist at USDA Agricultural Research Service, Jornada Experimental Range, Box 30003, NMSU, Dept. 3JER, Las Cruces, NM 88003-0003. Reldon Beck is Professor in Animal and Range Sciences, New Mexico State University, Box 30003, Dept. 3I, Las Cruces, NM 88003-0003.

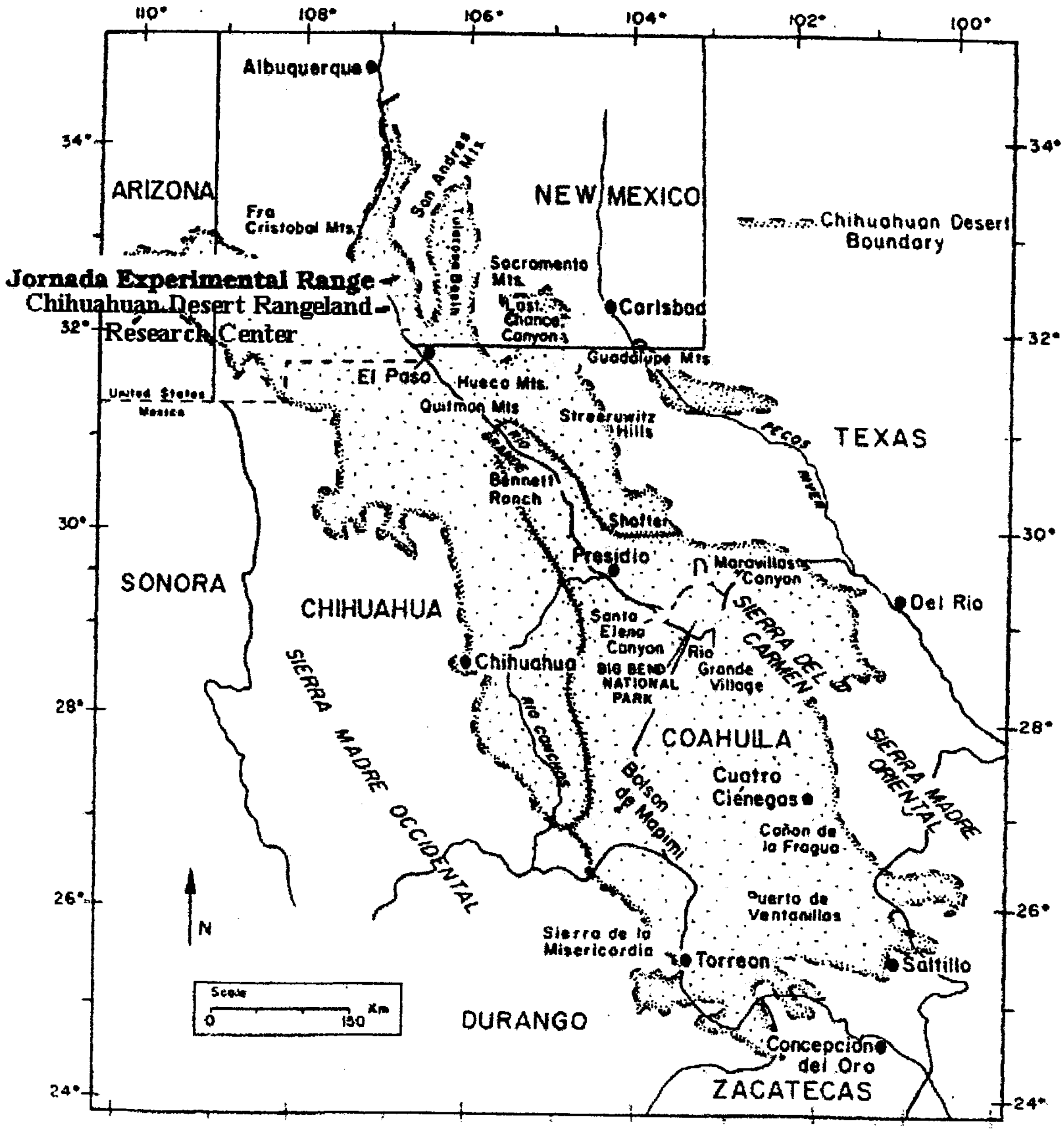

Figure 1—Boundary of the Chihuahuan Desert of North America.

(*Prosopis glandulosa* var. *glandulosa*), fourwing saltbush (*Atriplex canescens*), soaptree yucca (*Yucca elata*), and broom snakeweed (*Gutierrezia sarothrae*). Extensive dunes have developed where mesquite has invaded sandy soils. Low-lying areas with heavier soils, and which receive water from surface runoff, are dominated by tobosa (*Pleuraphis mutica*) and burrograss (*Scleropogon brevifolius*). Tarbush (*Flourensia cernua*) is a frequent dominant of these heavy soils. Slopes with gravelly soils near the mountains are typically dominated by creosotebush (*Larrea tridentata*). In years with favorable winter and spring moisture, many annual grasses and forbs are also abundant across soil types.

Within the mountains, shrub types are mixed. Major dominants include honey mesquite, creosotebush, sotol (*Fouquieria splendens*), ocotillo (*Dasylirion wheeleri*), and whitethorn (*Acacia constricta*). Some areas of scrub woodland are dominated by red-berry juniper (*Juniperus erythrocarpa*) and Mexican pinyon pine (*Pinus cembroides*).

The increase in brush on the Jornada Plain is well documented. A land survey made in 1858 included notes on soils and vegetation. From these notes, the relative abundance of brush types in 1858 was reconstructed. Extent of brush types was also determined from vegetative surveys made on the Jornada Plain in 1915, 1928, and 1963.

In 1858, good grass cover was present on more than 90 percent of the 58,492 ha studied. By 1963, less than 25 percent of the area had good grass cover. Table 1 shows the percentage of area occupied by dense (55 to 100 percent of perennial plant composition) brush cover of the major shrubs at various dates.

Table 1—Shrub increase in areas of the Jornada Basin during a 105 year period.

Vegetation cover[1]	1858	1915	1928	1963
	Percent			
Brush-free	58	25	23	0
Honey mesquite	5	24	22	50
Creosotebush	0	3	5	14
Tarbush	0	2	5	9

[1] Dense cover ≥ 55% of perennial plant composition.

Mesquite is the primary invader on sandy soils. Tarbush has increased on the heavier soils, and creosotebush occupies shallow and gravelly soils. Collectively, the spread of brush has been ubiquitous and rapid. As a result, range carrying capacities have been drastically lowered. Periodic droughts, unmanaged livestock grazing in the 19th century, and brush seed dispersal by humans, livestock, and many different wild species have all contributed to the spread of the shrubs. Brush has increased in permanent livestock exclosures erected during the 1930's demonstrating that brush invades grasslands even in the absence of livestock grazing. Once established, brush effectively monopolizes soil moisture and nutrients, and grass reestablishment is generally very limited without selective control of brush species. However, traditional brush control practices are expensive and frequently only of short-term effectiveness. New technologies are needed, but at present there are few economical management options for controlling continued brush encroachment.

Geology

The ages of geologic material in the Jornada vicinity range from Precambrian granites to Historical eolian and arroyo sediments. The Precambrian rocks are exposed on the east side of the San Andres and Organ Mountains where they have been uplifted thousands of meters by folding and faulting. Covering the Precambrian rocks are Paleozoic marine rocks, predominately limestones, that record shallow seas having spread across the once level Precambrian landscape. The San Andres and Franklin Mountains are mainly composed of these Paleozoic marine rocks.

Mesozoic rocks are less common, indicating uplift in the Las Cruces area until the Cretaceous when seas again spread across the area to deposit sandstones. Many Cretaceous rocks in southern New Mexico, however, are nonmarine and contain paleosols and dinosaur fossils. The Mesozoic ended and the Tertiary was ushered in by a period of mountain building—the Laramide orogeny—documented by bouldery alluvial fan deposits. Much of the Jornada Basin is filled with sediments derived from erosion of adjacent Laramide uplifts.

By middle Tertiary (ca. 30 million years ago), the Jornada region was a place of immense volcanic activity, as volcanism associated with the Organ Mountains produced sequences of igneous rocks over 3 km thick. Since the Dona Ana mountains are chemically and chronologically similar to the Organ Mountains, they are probably part of the same volcanic cauldron.

Following the middle Tertiary volcanism was the beginning of the last chapter of geologic evolution in the Jornada region: tectonic extension. The pulling apart of the crust formed the fault-block mountains in the region, such as the Franklin, San Andres, and Robledo mountains, as well as the intermontane basins between them. Movement continues and the mountains are still rising as testified by displacement of late Holocene alluvial fans along faults on the eastern side of the Organ and San Andres mountains. Many of the playas in the Jornada region have been produced by normal faults.

As the Tertiary ended and the Quaternary began, the ancestral Rio Grande was rapidly filling the Jornada, Mesilla, and Hueco basins with river sediment. At that time, the ancestral river emptied into a large lake, Lake Cabeza de Vaca, in northern Chihuahua. Carried along with the river sediment was datable pumice clasts from the Jemez volcanic center in northern New Mexico. One of these pumice layers has been uncovered west of the JER Headquarters. Around 750,000 years ago, Lake Cabeza de Vaca, like an overly full bathtub, spilled over its rim at El Paso, and northern Mexico was instantly robbed of a huge freshwater lake. Subsequently, the ancestral Rio Grande downcut through its sediments to eventually make the confined river valley present today. When the ancestral Rio Grande entrenched, like a giant drainage ditch, it lowered the regional ground water with it.

Tour

The trip across the Jornada plain included six stops (fig. 2). Stops were chosen to reflect a cross section of ecological and management-oriented research conducted on the approximately 100,000 ha devoted to field experimentation under the stewardship of NMSU and the ARS.

Stop 1. Creosotebush—Effects of Water and Nutrients

Experimental and descriptive studies have shown that in the Chihuahuan Desert, creosotebush growth is regulated as much by nitrogen availability as by water. Field experiments using two patterns of irrigation and one level of nitrogen fertilization were conducted to discern water and nitrogen interactions that control primary production of creosotebush. Irrigation provided as small, frequent events (6 mm/week) caused larger increases in vegetative production and fruit production than large, infrequent events (25 mm/month). Nitrogen fertilization plus small, frequent events resulted in the highest vegetative production and fruit production. These data provide the basis for understanding variation in creosotebush productivity measured over successive years.

Creosotebush production was significantly lower in the second wet year than in the first year of high rainfall. High biomass of annual plants produced during the first wet year provided the carbon inputs (as dead plant roots) that was the energy source for the soil microbiota that immobilized soil N during the second year. In the Chihuahuan Desert creosotebush production is limited by both soil moisture and

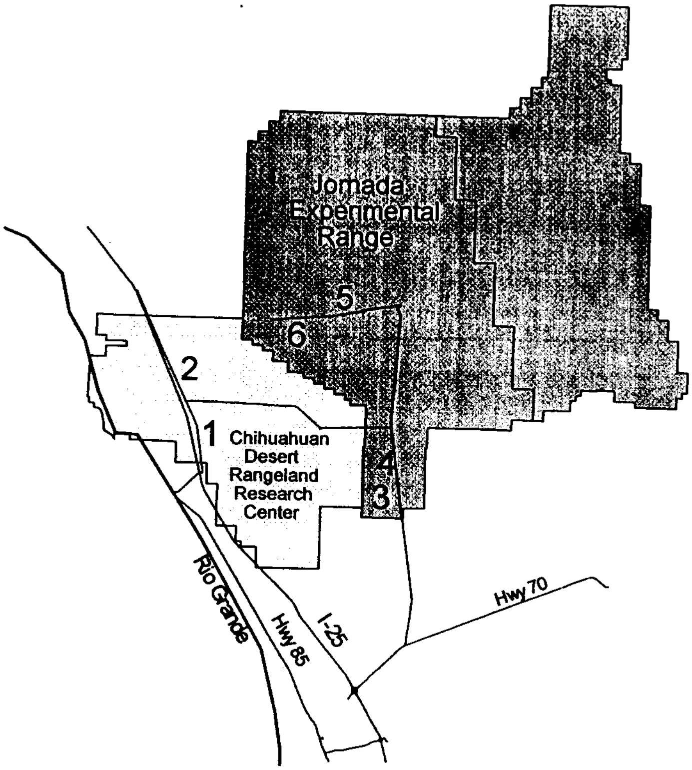

Figure 2—Jornada Basin tour route.

nitrogen availability, and patterns of rainfall appear to be more important than amount as a variable affecting productivity.

Several studies have demonstrated that much of the interplant variability in arthropod populations on creosotebush were related to foliar growth and foliar nitrogen content. Phytophagous sap-sucking insects accounted for most of the arthropods on creosotebush. When shrubs were selected that were judged to have higher foliar nitrogen (based on morphology and extent of below canopy litter layer), those shrubs supported higher insect populations than creosotebushes selected at random. Variations in rainfall patterns as produced by irrigation had little effect on creosotebush insect populations.

Stop 2. Pasture 15 on Chihuahuan Desert Rangeland Research Center

Grazing Study—A grazing study using cattle was initiated in 1967. The purpose of this study was to determine the type of plant response on pastures grazed only in a specific season each year as compared to a pasture grazed continuously yearlong. Annual rainfall is near 235 mm, with 53% falling from July through September. Amount of precipitation varies widely among years and, therefore, herbage production has varied from less than 5 kg/ha in 1994 to over 550 kg/ha in 1986. Because herbage production varies so much among years, there is considerable variation in animal performance, with calf crop averaging 83% and calf production averaging 3.2 kg/ha/yr. Because of the wide variation in rainfall patterns and herbage production, few differences in plant response exist between the two grazing strategies.

Mesquite—Mesquite populations have increased and expanded into neighboring grassland for the last 100 years. Considerable effort has been expended in research and management in learning how to control mesquite populations. Starting in the 1950's and continuing into the 1970's there were many herbicide treatments applied in the Jornada Basin for controlling mesquite. At this site individual plants were sprayed with 2,4,5-T. At that time the mesquite population was less than 125 plants/ha. Cost of the treatment was $2.82/ha. Rootkill of the treatment was 95%. Mesquite populations today in the sprayed area are still less than when it was controlled in 1958 (table 2).

Stop 3. Tarbush Community on the JER

The Jornada Experimental Range is one of 19 sites in the Long-Term Ecological Research (LTER) network, a set of locations for research into long-term and large-scale ecological processes, supported by the National Science Foundation. Ecosystems represented range from Alaskan tundra to Puerto Rican tropical forest, with two sites in Antarctica. The Jornada site represents the most xeric extreme in the network and is a valuable point of comparison for ecological studies done in other grassland and shrubland systems. The extensive history of research on this site (from early USDA work through the years of the International Biological Programme) make this one of the most truly long-term of the LTER sites.

LTER research is planned and carried out by a cooperative group of researchers from various institutions including Duke, Dartmouth, New Mexico State University, and the USDA's Agricultural Research Service. Initiated in 1981, LTER research at this site focused first on the role of soil water and nitrogen in determining patterns of production and dynamics in major plant and consumer species on a topographic gradient from the Dona Ana Mountains to a playa 3 km downslope.

In 1989, research was expanded to the general question of heterogeneity of soil resources (especially water and nitrogen) in a wider range of communities in the Jornada area. Scientists hypothesized that the conversion of semi-desert grassland to shrub-dominated ecosystems has resulted in a more patchy distribution of soil resources, and that the shrubs themselves reinforce this patchiness by positive feedback on resource redistribution (for example, infiltration, erosion, litter deposition). This alteration of resource distribution is suspected to be responsible for the difficulty in reversing the vegetation change.

This stop provided a look at one of the 15 sites currently being monitored—three sites from each of 5 major vegetation

Table 2—Changes in mesquite density, Pasture 15, CDRRC.

	Number mesquite/ha		
Treatment	**1982**	**1993**	**Percent increase**
Sprayed in 1958	44	61	39
Not sprayed	256	323	26

types (black grama grassland, creosotebush stands, mesquite-dominated areas, tarbush flats, and grassy playas). Data from these ecosystems are being used to answer questions about differences in productivity between grassland and shrubland systems, and about the relationship between plant diversity and ecosystem function in these arid lands.

The Jornada is one of a few LTER sites managed explicitly as a collaboration between academic scientists and Federal agency researchers (others include the Central Plains Experimental Range in Colorado, the Coweeta Hydrologic Laboratory in Georgia, and the Andrews Experimental Forest in Oregon). The synergy of this collaboration propels our research effort on the implications of vegetation change in the arid southwest and the ecological basis for sustainable management of dryland systems.

Stop 4. Plant/Animal Interactions

In this arid environment, encroaching shrubs are often chemically-defended. Grazing use of these shrubs is generally influenced by preingestive sensory cues and post ingestive consequences. Our studies of grazing preferences are based on the model outlined in figure 3. We utilize tarbush as the shrub for experimentation based upon this model.

To date, we have learned that tarbush's nutrient composition is similar to alfalfa, although nitrogen availability is less. Digestion studies showed that tarbush added to the diet improved utilization of low quality forages, a response largely due to the high nitrogen concentration of tarbush. Added nitrogen from tarbush also partially alleviated nutritional stress due to dietary intake of poor quality forages, a condition common during drought years. Results of toxicological studies have been variable. Tarbush leaves fed to ewe lambs up to 30% of the diet for 28 days did not appear to cause toxicosis; however, sheep fed 15% tarbush for 120 days (60 days pre- and post-weaning) developed muscular and liver lesions. Lesions observed included apoptosis, or individual cell death, in liver hepatocytes. However, in a subsequent study, 15% tarbush fed to ewes for 120 days did not elicit toxicosis. Work is currently being initiated to develop appropriate assays for isolation of potential toxicant(s).

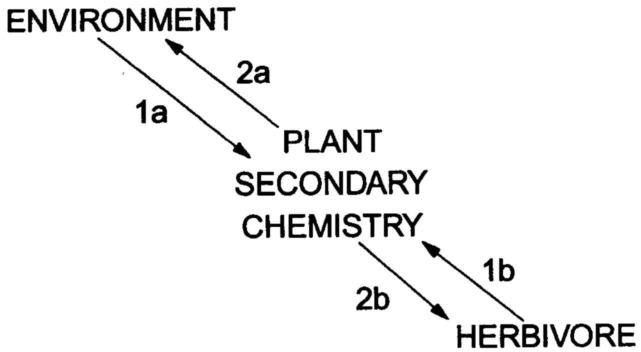

Figure 3—Central role of secondary chemistry of Chihuahuan Desert shrubs in plant-animal-environment interactions. Although plant secondary chemistry is genetically determined and a constitutive component of the plant, it is also plastic. Plant secondary chemistry profile and concentration can be altered by the environment and consumers. Environmental biotic and abiotic factors (phenology, light, water, nutrients, insects, small mammals, microbes, etc.) can modify plant chemistry (1a) and herbivores can modify secondary plant chemistry via induction (1b). Plant secondary chemistry has consequences to the environment and to consumers. Plant secondary chemistry affects the environment by allelopathy, soil/litter accumulation, soil microbe activity, nutrient sequestering, etc. (2a), and plant secondary chemistry affects diet selection, behavior and physiology (learning, postingestive consequences, metabolic effects, toxicities, etc.) of herbivores (2b).

Despite the nutritional value of tarbush, domestic herbivores generally eat tarbush only in limited amounts. Experiments comparing the diets of beef cattle, sheep, goats, camels, guanacos and llamas revealed limited use of tarbush. Sheep and goats exhibit greater use of tarbush, with it constituting between zero and 15% of their diet. Studies using sheep found considerable variation in animal preference for tarbush. Some tarbush plants were readily eaten while others were avoided, and differences in plant palatability were related to leaf surface chemistry. Specific mono- and sesquiterpenes have been identified that allow prediction of whether a tarbush plant will be browsed. Studies directed toward selecting animals exhibiting greater preference for tarbush and identifying factors influencing their diet selection are ongoing.

Several biologically potent compounds in tarbush leaves, including compounds known to have analgesic, herbicidal, insecticidal, nematocidal, neuroactive and neoplastic activity have been identified. Some of these compounds may explain the use of tarbush as a curative for digestive disorders by people in Mexico and more recently in the United States. Additionally, compounds causing apoptosis are of interest to researchers studying the role of individual cell death in embryology, autoimmune diseases and fertility. Researchers from the Jornada Experimental Range are working with researchers at the University of New Mexico Medical School studying apoptosis. We now have an organic chemist exploring the natural products chemistry of tarbush and several other desert plant species.

Stop 5. Natural Revegetation Exclosure

In 1934, Jornada scientists established a one section (256 ha) exclosure along an ecotone between black grama dominated rangeland and mesquite dominated rangeland. Their assumption was that the black grama grassland would become reestablished with livestock exclusion. The entire exclosure today is now dominated by mesquite. Much of the remaining black grama failed to survive the extended drought during the 1950's.

In the early 1930's, scientists at the Jornada Experimental Range were concerned with the spread of mesquite and concomitant wind erosion. As part of their research program, transects were established in mesquite dunelands and on ecotones between grassland and mesquite dunelands. Soil levels were marked on a large number of grid and transect stakes. This farsighted action provided a unique opportunity to quantify soil movement. Soil levels at the

Table 3—Deposition and deflation of soil in 1935 and 1980 at 105 grid stakes on the 259-ha natural revegetation exclosure where soil levels were marked in 1933, and 1980 soil levels at 113 transect stakes on the exclosure on which soil levels were marked in 1935.

Database	Year of measurement	Soil movement category	Number of points	Maximum	Minimum	Mean	Net Loss (–) or Gain (+) (cm)
				------	cm	------	
Grid stakes	1935	No change	9				
		Deposition	36	6.0	0	1.1	
		Deflation	60	4.9	0	1.4	–0.4
	1980	Deposition	33	78.3	1.8	23.8	
		Deflation	72	61.9*	0.9	17.4	–4.6*
Transect stakes	1980	Deposition	43	78.6	0.6	2.5	
		Deflation	70	45.1*	0.9	2.1	–3.5*

*Represent minimum values because one stake was completely excavated by wind erosion.
(Adapted from Gibbens and others 1983).

original stakes were remeasured in 1980. Soil movement during the 45 year period shows that mesquite dunelands, while having an appearance of stability, are actually a dynamic, constantly shifting system (table 3).

The magnitude of soil movement within the mesquite dunelands indicates that considerable degradation of the soils as a plant growth medium has occurred. Other studies have identified the soil components lost in suspension as being predominately from the silt and clay fractions as the dunelands are "churned" by wind erosion. Loss of silts and clays would reduce the soil binding properties imparted by these two size fractions, and the remaining fraction would be even more susceptible to wind erosion. In this arid environment, appreciable changes in water holding capacity alone could be a factor causing shifts in vegetation associated with the mesquite dunes and in potential site productivity. Identification of the redistribution and depletion of soil biota within the mesquite dunelands is the object of continuing studies.

Similar to many semiarid lands and deserts, soils in the Jornada region accumulate calcium carbonate (caliche). The older the soil, the more calcium carbonate it accumulates. Leland Gile (retired scientist formerly with the then Soil Conservation Service) and others defined a sequence of carbonate stages related to soil age. Young soils pass from being non-calcareous to having stage I filaments, then stage II nodules, then a stage III plugged horizon, and finally a stage IV horizon composed of a laminar zone formed atop the carbonate plugged horizon. A stage IV carbonate horizon takes about 500,000 years to form in non-gravelly soils, but much less time, about 50,000 years, in gravelly soils. The gravelly soils become cemented faster by carbonate because they have less pore space and less surface area than finer textured soils.

Although caliche horizons are often a barrier to root growth, caliche is permeable to water in most cases. Therefore, caliche horizons have the ability to absorb and store water, and possibly nutrients, and thus play an important role in rangeland vegetation dynamics.

Hundreds of papers have been written about caliche formation, which in the southwestern US is predominately the result of atmospheric additions of calcareous dust and Ca^{2+} dissolved in rain water mediated, in part, by soil microorganisms. Caliche has recently taken on additional importance because of its carbon storage capacity and its isotopic signatures that provide information about vegetation changes in the past.

Although caliche formation is a prominent pedogenic process in semiarid and arid soils, other processes such as chemical weathering, clay mineralogy, water holding capacities, bioturbation, mineral-microbe-root relations, and erosion-sedimentation have major impacts on rangeland vegetation. Many questions involving below-ground mechanisms and their link to the amazing drought tolerance of many wildland shrubs remain to be answered.

Stop 6. Multiple Stressor Experiment

In 1993, an experiment to address empirical tests of the sensitivity of a variety of indicators of ecosystem health as measures of exposure to single and multiple environmental stressors was initiated. The Environmental Protection Agency co-funds this research with the Jornada Experimental Range and the LTER program. The experiment was initiated in August 1993 with the establishment of plots and the collection of baseline data. The experiment was designed to address hypotheses concerning the effects of environmental stressors on ecosystem properties and processes: (1) exposure to more than a single stressor results in simple additive responses and (2) removal of invasive shrubs, such as mesquite, reduces the impact of other stressors on a desert grassland ecosystem. There are a number of sub-hypotheses concerning the effects of stressors on selected populations and ecosystem properties and processes.

To date, the data show some interesting patterns. Small mammals have been affected by shrub removal with some species disappearing on plots where shrubs were removed (wood rats most affected). There has been no change in the ant community as a result of shrub removal. Soil depth varies dramatically at a scale of meters, not 10's of meters, as we originally hypothesized; and there were no obvious patterns of soil depth and distribution of perennial plants.

Acknowledgments

The authors wish to thank Curtis Monger, Walt Whitford, Laura Huenneke, Bill Schlesinger, Ed Fredrickson, Dean Anderson, Dale Gillette, and Jeff Herrick for their participation in the field tour and contribution to these field notes. Thanks are also expressed to the many people who contributed greatly to the logistics of the tour including Barbara Nolen, Clyde Yarbrough, Calvin Bailey, Ron Aaltonen, Valerie Gamboa, and Marianne Jenson.

Additional information on the research programs in the Jornada Basin can be accessed at three locations on the Internet at:

http://www.nmsu.edu/~jornada
http://atlantic.evsc.virginia.edu/regionalization/jrn.html
http://shamu.psl.nmsu.edu/Jornada.html

These home pages outline current research objectives and bibliographies of prior published research.

References

Buck, B.J. 1993. Deterioration of paleoclimate in the late Cretaceous, indicated by paleosols in the McRae Formation, south-central New Mexico. M.S. Thesis, New Mexico State University, Las Cruces, NM.

Buffington, L.C. and C.H. Herbel. 1965. Vegetational changes on a semidesert grassland range from 1858 to 1963. Ecol. Monogr. 35:139-164.

Cerling, T.E. 1984. The stable isotopic composition of modern soil carbonate and its relationship to climate. Earth and Planetary Science Letters. 71:229-240.

Cunningham, G.L. and J.H. Burk. 1973. The effect of carbonate deposition layers ("cliche") on the water status of *Larrea divaricata*. The Am. Midland Naturalist. 90:474-480.

Gibbens, R.P., J.M. Tromble, J.T. Hennessy and M. Cardenas. 1983. Soil movement in mesquite dunelands and former grasslands of southern New Mexico from 1933 to 1980. J. Range Manage. 36:145-148.

Gile, L.H. 1961. A classification of Ca horizons in the soils of a desert region, Dona Ana County, New Mexico. Soil Sci. Soc. Am. Proc. 25:52-61.

Gile, L.H. 1994. Soils, geomorphology, and multiple displacements along the Organ Mountains fault in southern New Mexico. Bulletin 133. New Mexico Bureau of Mines and Mineral Resources, Socorro, NM.

Gile, L.H. and R.B. Grossman. 1979. The Desert Project soil monograph. Doc. No. PB80-135304. National Technical Information Service, Springfield, VA.

Gile, L.H., F.F. Peterson, and R.B. Grossman. 1966. Morphological and genetic sequences of carbonate accumulation in desert soils. Soil Scienc. 101:347-360.

Gile, L.H., J.W. Hawley, and R. B. Grossman. 1981. Soils and geomorphology in the Basin and Range area of southern New Mexico—Guidebook to the Desert Project. Memoir 39. New Mexico Bureau of Mines and Mineral Resources, Socorro, NM.

Hawley, J.W. 1975. Quaternary history of Dona Ana County region, south-central New Mexico. p. 139-150. New Mexico Geological Society, guidebook 26th field conference, Socorro, NM.

Hennessy, J.T., R.P. Gibbens, J.M. Tromble, and M. Cardenas. 1983. Water properties of caliche. J. Range Management. 36: 723-726.

Mack, G.H. 1992. Paleosols as an indicator of climatic change at the early-late Cretaceous boundary, southwestern New Mexico. Journal of Sedimentary Petrology. 62:483-494.

Mack, G.H., S.L. Salyards, and W.C. James. 1993. Magnetostratigraphy of the Plio-Pleistocene Camp Rice and Palomas Formations in the Rio Grande rift of southern New Mexico. Am. Journal of Science. 292:49-77.

Monger, H.C., L.A. Daugherty, W.C. Lindemann, and C.M. Liddell. 1991. Microbial precipitation of pedogenic calcite. Geology 19: 997-1000.

Quade, J., T.E. Cerling, and J.R. Bowman. 1989. Systematic variations in carbon and oxygen isotopic composition of pedogenic carbonate along elevation transects in southern Great Basin, United States. Geological Soc. Am. Bulletin. 101:464-475.

Seager, W.R. 1981. Geology of Organ mountains and southern San Andres mountains, New Mexico. Memoir 36. New Mexico Bureau of Mines and Mineral Resources, Socorro, NM.

Seager, W.R., J.W. Hawley, F.F. Kottlowski, S.A. Kelley. 1987. Geology of the east half of Las Cruces and northeast El Paso 1°x2° sheets, New Mexico. Geologic Map 57. New Mexico Bureau of Mines and Mineral Resources, Socorro, NM.

Schlesinger, W.H. 1982. Carbon storage in the caliche of arid soils: A case study from Arizona. Soil Sci. 133:247-255.

Schlesinger, W.H. 1985. The formation of caliche in soils of the Mojave Desert, California. Geochemica et Cosmochemica Acta. 49:57-66.

Schlesinger, W.H. 1995. An overview of the carbon cycle. p. 9-25. In R. Lai and others (eds.) Soils and Global Change. CRC Lewis Publishers, London.

Schlesinger, W.H., J.F. Reynolds, G.L. Cunningham, L.F. Huenneke, W.M. Jarrell, R.A. Virginia, and W.G. Whitford. 1990. Biological feedbacks in global desertification. Science. 247:1043-1048.

Strain, W.S. 1966. Blancan mammalian fauna and Pleistocene formations, Hudspeth County, Texas. The University of Texas (Austin), Texas Memorial Museum, Bull. 10.