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The near-ubiquitous pedogenic world of mesquite roots in an arid basin floor

L.H. Gile*‡, R.P. Gibbens† & J.M. Lenz†

**Soil Survey Investigations, USDA-NRCS, Las Cruces, New Mexico, U.S.A.*
†Jornada Experimental Range, USDA-ARS, Las Cruces, New Mexico, U.S.A.

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A major invasion of grassland by shrubs began about 1850 A.D. in many desert areas of southern New Mexico. Mesquite (*Prosopis glandulosa*) is the most numerous of these invading shrubs in a studied basin floor. Mesquite roots readily penetrated all soil horizons except for continuously indurated petrocalcic horizons. However, roots grew along the top of petrocalcic horizons and in places found locations for penetration, such as cracks and pipes, with numerous, often upward-growing roots enroute to utilize the sparse precipitation. At another site, mesquite roots descended to a depth of at least 5·5 m. Although the spread of mesquite seed by cattle was a major factor in the spread of mesquite, its successful establishment over large areas is apparently due to the ability of mesquite roots to adapt to a wide variety of soils and soil conditions to take advantage of the sparse precipitation; to their ability to greatly proliferate while spreading laterally over long distances; to grow upward and take advantage of small precipitation events that only wet the soil to depths of a few centimeters; and to descend to great depths along cracks and other openings in the soil, down which soil water also penetrates, and thus to their ability to utilize available water at all depths.

Keywords: coppice dunes; petrocalcic horizons; pipes; Haplargids; Calciargids; Torripsamments; Petrocalcids; Haplocalcids

Introduction

Widespread invasion of grassland by shrubs in desert areas of southern New Mexico since about 1850 A.D. has been documented by a number of authors, e.g. Gardner (1951), Buffington & Herbel (1965), and York & Dick-Peddie (1969). Major shrub invaders cited were creosotebush (*Larrea tridentata*), tarbush (*Flourensia cernua*), and mesquite (*Prosopis glandulosa*). In transects along the Rio Grande Valley, Gardner (1951) found creosotebush to be dominant, with small amounts of mesquite and tarbush. In a study on the Jornada Experimental Range, most of which is in a broad

‡Present address: 2600 Desert Drive, Las Cruces, New Mexico 88001, U.S.A.

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basin floor, Buffington & Herbel (1965) found mesquite to be the most common shrub, with smaller areas of tarbush and creosotebush. Probably because of the difficulty of the task, few excavations of mesquite roots have been made (Cannon, 1911; Ludwig, 1977; Heitschmidt *et al.*, 1988). The objectives of this study were to characterize the root systems of mesquite, illustrate some of the soils in which the roots occur, relate root occurrence to soil characteristics, and present the genetic background leading to pedogenic control on the disposition of mesquite roots. Both the main study area, with dunes, and a smaller playa study area are in the Jornada Experimental Range, in the Basin and Range country of southern New Mexico (Fig. 1).

Materials and methods

The main study area is in the broad floor of the Jornada del Muerto Basin, on La Mesa

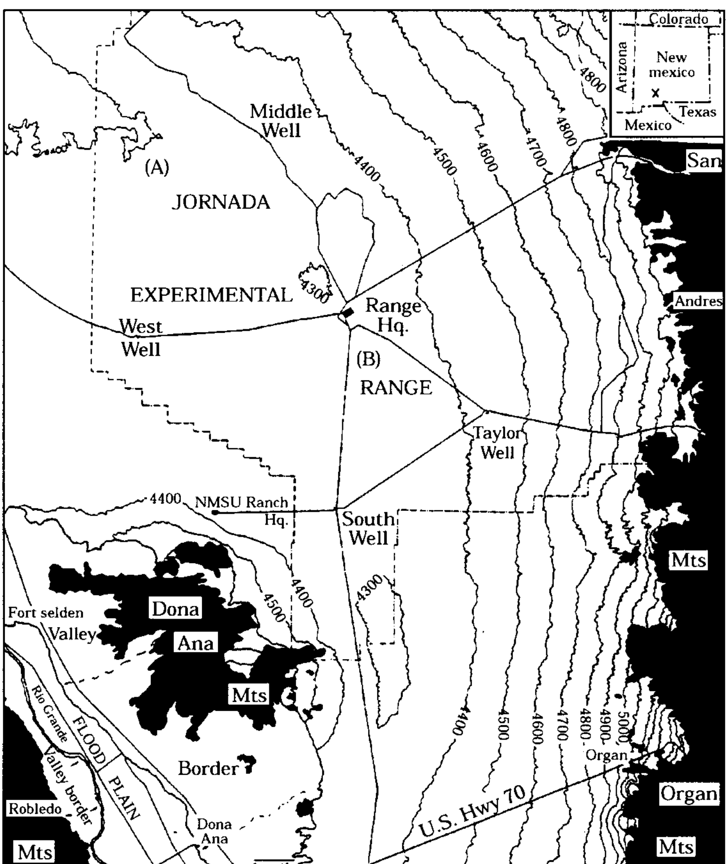

Figure 1. Map locating the study areas in the Jornada Experimental Range, southern New Mexico. (A) Indicates the main study area; (B) indicates the playa study. The Rio Grande Valley is on the lower left. Location in New Mexico shown in upper right. Contour intervals are in feet.

surface of middle to early Pleistocene age (Ruhe, 1967; Hawley & Kottlowski, 1969; Gile *et al.*, 1981; Mack *et al.*, 1993). Before the Rio Grande Valley was cut in middle to early Pleistocene time, the basin floor was a broad flood plain and distributary system of the ancestral Rio Grande. Except for Historical coppice dunes (Melton, 1940; Buffington & Herbel, 1965; Gile, 1966), soil parent materials are basin-floor sediments deposited by the ancestral river. These sediments are the fluvial facies of the Camp Rice Formation (Hawley, 1981; Mack *et al.*, 1993).

Relief of La Mesa surface ranges from level to gently undulating; the surface has been faulted and contains two named faults, the Jornada and Jornada Draw faults (Seager *et al.*, 1987; Seager & Mack, 1995). Slope at the main study area is 2% to the north. The study area is close to the south end of the Jornada Draw fault (Seager & Mack, 1995), not far from the north end of a branch of the Jornada fault (Seager *et al.*, 1987; B. Seager, pers. comm., 1995), and is tentatively considered to be on a fault scarp associated with one of the two faults.

Precipitation at the Range Headquarters (Fig. 1) averages 247 mm annually, and about half of this occurs between 1 July and 30 September. The soils are generally dry for long periods in the late spring and early summer. Summers are hot; mean temperature for July, the hottest month, is 26°C. Winters are mild. January, the coldest month, has a mean temperature of 6°C.

Vegetation on the coppice dunes is mostly mesquite, with a few four-wing saltbush (*Atriplex canescens*). Areas between dunes are largely barren; in places there are a few perennial plants, e.g. broom snakeweed (*Gutierrezia sarothrae*), fluffgrass (*Dasyochloa pulchella*), mesa dropseed (*Sporobolus flexuosus*) and bush muhly (*Muhlenbergia porteri*). Annual plants, such as Russian thistle (*Salsola australis*), are sometimes abundant.

Soil classification follows the Soil Survey Staff (1994; Table 1). Horizon designations follow the Soil Survey Division Staff (1993) except for the K horizon nomenclature (Gile *et al.*, 1965). Stages of carbonate accumulation follow Gile *et al.* (1966). Laboratory analyses were done by the National Soil Survey Laboratory in Lincoln, NE. Figure 2 is a soil map showing soil occurrence in the study area and locates four study trenches, the sampled pedons, and an excavated coppice dune from which mesquite roots were traced laterally.

Roots were excavated using a sprayer equipped with two hoses and spray wands which could be adjusted to deliver either a fine, gentle spray or a solid stream of water. Exposed roots were mapped on graph paper at a scale of 1 inch = 1 m or, if more detail was desired, at a scale of 1 inch = 10 cm. Root diameters were measured with a digital caliper.

Main study area

The excavated coppice dune

The excavated coppice dune had soils like those of the map unit designated Hueco soils, overblown phase (Fig. 2). Examination of dunes in and just north of the study area showed that they consist of young, stratified sandy sediments of Historical age (1850 A.D. to present, Gile *et al.*, 1981). Land survey notes and grazing history indicate that the dunes must have formed largely since the 1880s when deep wells in the Jornada basin floor made water available for cattle, numbers of which increased greatly (Buffington & Herbel, 1965). Because the dunes are prominent in aerial photographs taken in 1936 they must have formed mostly between 1936 and 1880s. No pre-Historical, post-La Mesa sediments (e.g. the II material of Gile, 1966) were found between the dune sediments and the underlying soils of La Mesa age.

The excavated coppice dune (Figs 2–4) was 6·3 m long, 4 m wide and 1·1 m in height. Mesquite stems averaging 0·6 m in height covered the dune and near the west

Table 1. *Classification and diagnostic horizons and features of soils discussed in this report*

Order	Suborder	Great group	Subgroup	Family	Series, phase or analog, and sampled pedon
Aridisols	**Argids** Have argillic but no petrocalcic horizon within 100 cm	**Calciargids** Have calcic horizon within 150 cm	**Typic Calciargids** Have aridic moisture regime	Coarse-loamy	Yucca
					Yucca, deep analog
					Yucca, argillic analog (94–4)
		Haplargids No calcic horizon within 100 cm	**Typic Haplargids** Have aridic moisture regime	Sandy	Sonoita, sandy analog (94–3) and its overblown phase
		Petroargids Have petrocalcic horizon between 100 and 150 cm	**Typic Petroargids** Have aridic moisture regime	Coarse-loamy	Rotura
	Calcids Have calcic or petrocalcic horizons within 100 cm; no argillic horizon within 100 cm unless petrocalcic horizon is within 100 cm	**Petrocalcids** Have petrocalcic horizon within 100 cm	**Typic Petrocalcids** Have aridic moisture regime	Coarse-loamy	Harrisburg
				Coarse-loamy, shallow	Simona
				Sandy, shallow	Tonuco, moderately deep analog
			Argic Petrocalcids Have argillic horizon within 100 cm	Coarse-loamy	Hueco and its overblown phase
				Coarse-loamy, shallow	Cruces (94–1)

Table 1. *(continued)*

Order	Suborder	Great group	Subgroup	Family	Series, phase or analog, and sampled pedon
		Haplocalcids Have calcic horizon within 100 cm	**Typic Haplocalcids** Have aridic moisture regime	Coarse-loamy	Whitlock
Entisols	**Psamments** Have <35% by volume of rock fragments and lfs or coarser texture	**Torripsamments** Have torric (aridic) moisture regime	**Typic** Torripsamments	Sandy	Bluepoint (94–2) and its overblown phase
				Sandy	Bluepoint, thin analog

All soils have mixed mineralogy and are in the thermic temperatures class (see Soil Survey Staff, 1994, for complete definitions of diagnostic horizons and features). Bluepoint, Cruces, Harrisburg, Hueco, Simona, Sonoita and Whitlock are established series; the others are tentative. The term variant has been discontinued (Soil Survey Division Staff, 1993) and is here replaced by analog for informal use. Bluepoint soils have sandy textures to at least 1 m depth and occur both in dunes and in pipes with sandy textures that are thick enough. Bluepoint, thin analog is similar to Bluepoint but has a buried soil at depths between 50 and 100 cm. Overblown phases have up to 50 cm of Historical dune sediments over the named soil. The deep analog of Yucca has a calcic horizon between 100 and 150 cm depth; the argillic analog of Yucca has an argillic horizon below the calcic horizon instead of above it. The moderately deep analog of Tonuco has a petrocalcic horizon between 50 and 100 cm depth.

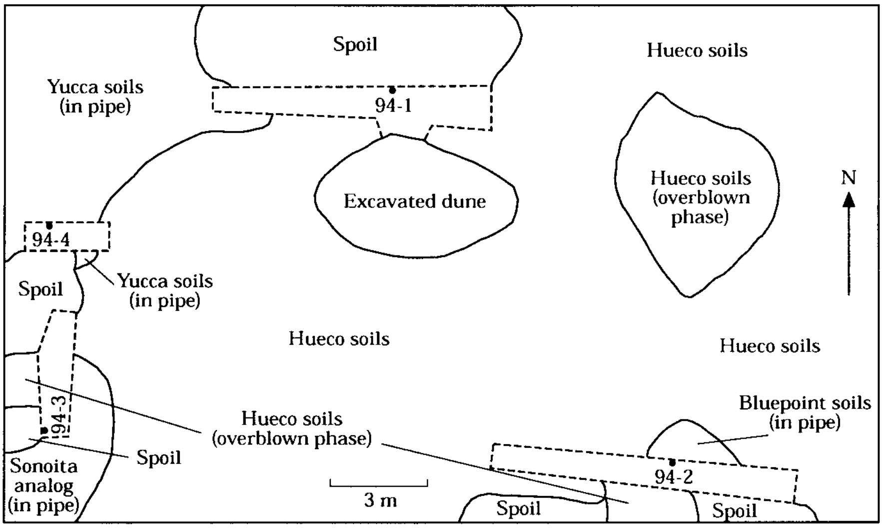

Figure 2. Soil map of the study area. In addition to the soil in the map unit name, which is dominant, the map units contain minor areas of other soils (in parentheses) as follows (see Table 1 for classification): Bluepoint soils (Rotura); Heuco soils (Bluepoint, Cruces, Harrisburg, Simona, Tonuco analog, Yucca, deep analog, Whitlock); Hueco soils, overblown phase (Bluepoint, Bluepoint, thin analog, and overblown phases of Bluepoint and Sonoita); Sonoita analog (Sonoita); Yucca soils (Yucca, argillic analog). Dashed lines delineate study trenches, and numbers (e.g. 94-1) locate the sampling sites.

end there was a very large four-wing saltbush plant 1·6 m in height. A few plants of mesa dropseed were growing on the dune. Oven-dry (60°C), above-ground, live mesquite biomass totaled 11·3 kg, and above-ground dead biomass was 5·9 kg. Excavation revealed that the mesquite component of the dune originated from four separate plants. Three of these were large and probably of comparable age and one at the periphery of the dune was much smaller and younger. As the dune formed, mesquite branches were buried but continued to grow. These large, buried branches (Fig. 4) gave rise to emergent branches which formed the above-ground part of the mesquite plants. The live, buried branches (oven-dry, ash-free weight) totaled 16·2 kg, exceeding the emergent live biomass. Buried, dead branch biomass was only 1 kg but probably during the life of the dune several kilograms of material had decayed. The four root crowns weighed 6·4 kg. The centres of the main trunks of the large mesquite plants had decayed and it was not possible to obtain cross-sections for ring counts. Cross-sections of the buried branches revealed that growth rings were so poorly defined that only an estimate of > 50 years of age could be made.

Dune root systems

The four-wing saltbush plant had a well-developed tap root which extended to a depth of 57 cm at which point it split into three branches. One very large (5 × 7 cm) horizontal branch arose at a depth of 10 cm. There were 370 first order branches arising from the tap root and over half of these originated between depths of 20 and 40 cm. Only 32 of the first order branches were > 2 mm in diameter. Most of the roots < 2 mm diameter were < 1 m in length. However, the larger, extensively branched roots extended up to 5 m from the plant. Above-ground live and dead biomass for the four-wing saltbush was 7·6 and 3·9 kg, respectively.

The three old mesquite plants had well-developed tap roots which had penetrated to the level of the petrocalcic horizon. However, in every case, the lower portions of the tap roots were dead and decayed. Thus, the active root systems were composed of a few roots originating from the root crowns and, collectively, about 230 adventitious roots ranging in diameter from 0·8 to 34 mm arising from the buried branches.

The soil in the dune was permeated with a mass of fine roots of mesquite and four-wing saltbush. It has been postulated that shrubs cause heterogeneity to develop in soil resources by creating self-augmenting 'islands of fertility' (Schlesinger *et al.*, 1990). The abundance of roots in the elevated portion of the dune supports this hypothesis because it is obvious that the dune itself was a major source of water and nutrients for the shrubs.

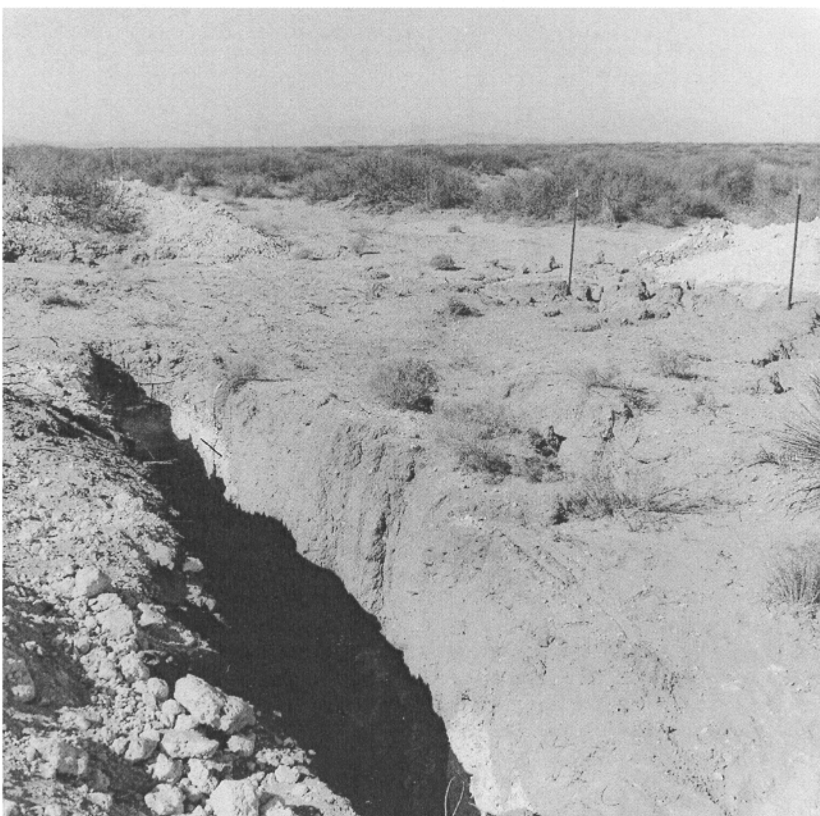

Figure 3. The main study area after excavation of the mesquite dune, marked by the two stakes to the right. The excavated dune was like those in the background. The light-colored spoil beyond the stakes is from trench 94-1 (see Fig. 2). At upper left are parts of trenches 93-3 and 93-4, with spoil just beyond. In the foreground is trench 94-2, with a large pipe in the centre and discontinuous petrocalcic horizons on both sides of the pipe. The sampled Bluepoint pedon 94-2 (see text discussion) is in approximately the centre of the pipe. The line on the tape on the right side of the trench marks a depth of 2 feet. (Photographed January 1994).

Lateral extension of mesquite roots

Thirteen mesquite roots with diameters ranging from 8 to 34 mm were traced outward from the dune. These extended from 4·5 to 16 m from point of origin (Fig. 4). Measured along the path of the root, the longest root excavated was 22 m in length. The larger roots typically bi-, tri-, or quadra-furcated into branches of slightly smaller diameters at highly variable distances from the point of origin. Only a few of the many branches could be followed and the policy was to follow the largest branch. The horizontal roots typically grew just above the petrocalcic horizons at depths ranging from 7 to 80 cm.

Roots from adjacent coppice dunes were frequently encountered during excavation of the horizontal roots, indicating a great deal of overlap of root systems in the open spaces between dunes. No roots from neighboring dunes were detected within the excavated dune, but one root from the excavated dune was traced into a neighboring dune. It was observed that rodents burrowing into the dune frequently severed roots. A number of dead branches of all diameters were found on mesquite roots extending outward from the dune (Fig. 4). Evidently the root turnover rate was fairly high.

All of the roots portrayed in Fig. 4 had a large number of small, relatively short branches. An unusual feature was that many of these branches grew vertically upward rather than horizontally or downward (Fig. 5). These upward-growing roots originated at depths up to 50 cm and ascended to within 4 cm of the soil surface. Upward-growing roots were found on a mesquite tree in Texas but were largely confined to the area under the tree canopy (Heitschmidt *et al.*, 1988). Upward-growing roots were also found in crucifixion thorn (*Koeberlinia spinosa* Zucc.) in the Jornada Experimental

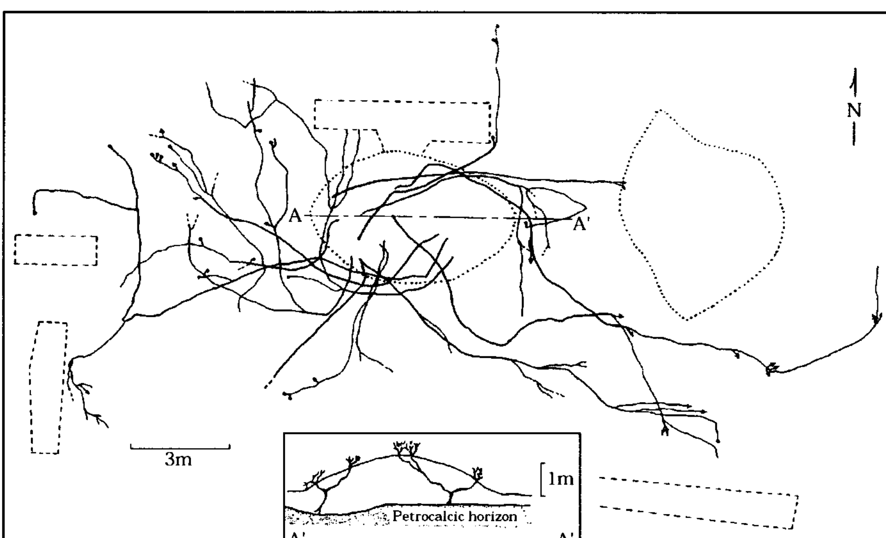

Figure 4. Map of horizontal distribution of mesquite roots extending outward from the excavated dune. Small solid circles denote a vertical downward extension of roots; dashes indicate dead roots, and arrows indicate live roots which were not followed. Dotted lines represent dune boundaries and dashed lines delineate trenches. Trench 94-1 was lengthened to the dimensions shown in Fig. 2 after root excavations were completed. Vertical profile of dune along line A-A' is shown in insert with a diagrammatic representation of buried and emergent mesquite branches.

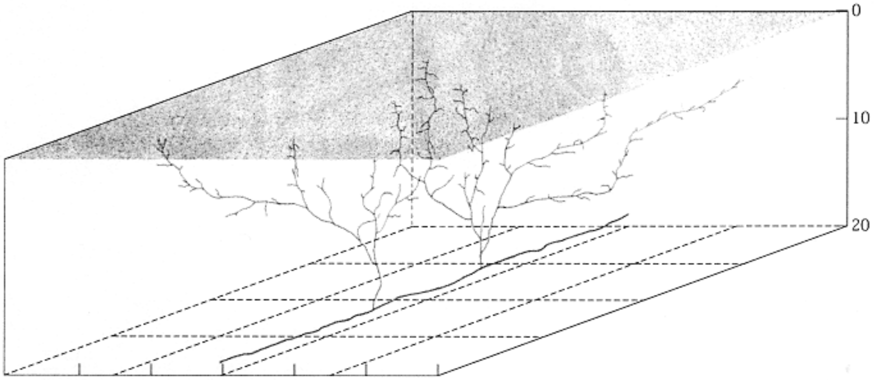

Figure 5. Three-dimensional diagram showing upward-growing mesquite roots, which extended to within 4 cm of the soil surface. Such upward-growing roots were found arising at depths up to 50 cm. Terminal branches were about 0·4 mm in diameter. Shaded area denotes the soil surface.

Range (Gile *et al.*, 1995). The abundance of upward-growing roots of mesquite in this arid environment means that the root system is well adapted to take advantage of relatively frequent small precipitation events that only wet the soil to a depth of a few centimeters.

In the trench just north of the excavated dune (Fig. 2), roots of both mesquite and four-wing saltbush penetrated cracks in the petrocalcic horizon of the Cruces soils, to be discussed in the next section, and were traced to a depth of 3 m. At this depth, the roots were still about 5 mm in diameter and probably penetrated deeper but were not followed due to time constraints.

The ancient soils of La Mesa and mesquite roots

Work on the magnetostratigraphy indicates that many soils of La Mesa surface are 0·78 to 0·9-million-years-old (Mack *et al.*, 1993). The following sections present the genetic background that led to pedogenic control of root distribution in these ancient soils.

The Argic Petrocalcid, Cruces 94-1

The Cruces soils, similar to Hueco soils but in a shallow family (Table 1), occur just north of the excavated dune in the vicinity of pedon 94-1 (Fig. 2). Data for a Cruces pedon overlain by a thin deposit of stratified sand are given in Table 2, and illustrate properties of one of the thick soils common on La Mesa surface.

Beneath the superficial sand the sampled pedon has a thin A horizon, an argillic (Bt) horizon that is underlain by a petrocalcic (Km) horizon, and a C horizon that is sandy and noncalcareous in part. The petrocalcic horizon is characterized by very high carbonate content and is extremely hard (Table 2). It cannot be penetrated by mesquite roots except along cracks and other openings such as pipes (discussed later).

In places the K horizon has scattered reddish brown parts of Bt material that is noncalcareous or effervesces weakly, and occurs above cemented zones of carbonate

Table 2. *Characteristics of the Argic Petrocalcid Cruces and the Typic Torripsamment Bluepoint*

Horizon	Depth (cm)	Hue	Value/chroma Dry	Value/chroma Moist	Dry consistence	Texture	Sand 2–0·05 mm (%)	Silt 0·05–0·002 mm (%)	Clay < 0·002 mm (%)	Organic C (%)	$CaCO_3$ equiv. < 2 mm (%)
Cruces 94–1											
C	0–10	5YR	5·5/4	4/4	sh	s	90	5	5	0·27	–
BAtb	10–16	5YR	6/4	5/4	sh	fsl	80	8	12	0·21	2
Btk1b	16–26	5YR	6/4	4·5/4	sh	fsl	76	10	14	0·24	4
Btk2b	26–36	5YR	6/5	4·5/4	h,vh	fsl	72	11	17	0·26	4
Btk3b	36–42	5YR	6/4	4·5/4	h	fsl	74	9	17	0·25	4
K1b	42–51	7·5YR	9/2	8/2	eh	vg	74	11	16	0·41	63
K21mb	51–61	7·5YR	8/1	7/3	eh		76	14	10	0·34	74
K22mb	61–72	7·5YR	9/3	8/3	eh		76	14	10	0·27	71
K23mb	72–88	7·5YR	9/2	8/2	eh		67	18	15	0·16	56
K24mb	88–114	7·5YR	9/2	8/2	eh		67	19	15	0·12	60
K25b	104–122	7·5YR	9/2	8/2	eh		75	16	9	0·14	69
K26mb	122–150	7·5YR	9/2	8/2	eh		73	18	8	0·11	53
K27b	150–173	7·5YR	8/2	7/3	eh		84	13	4	0·07	26
K28b	173–195	7·5YR	8/2	7/3	eh		84	11	4	0·07	23
K29mb	195–212	7·5YR	9/2	8/2	eh		86	10	4	0·10	33
K31b	212–230	10YR	9/2	8/2	eh		84	13	4	0·05	40
K32b	230–253	10YR	9/3	8/3	eh	vgls	80	17	3	0·06	33
K33b	253–302	10YR	9/2	8/2	s	vgls	78	18	4	0·05	33
Cb	302–322	10YR	7/2	5/2	s	s	97	3	TR	TR	–
Ckb	322–352	10YR	7/2	5/2	s	s	96	4	TR	0·02	1
Bluepoint 94–2											
A	0–5	6YR	5·5/4	4/4	s,sh	ls	84	9	8	0·20	1
Bk1	5–23	6YR	5·5/4	4/4	s,sh	ls	87	7	6	0·19	1
Bk2	23–42	6YR	5·5/4	4/4	sh	ls	88	7	6	0·16	2
Bk3	42–65	6YR	6/4	4·5/4	sh,h	ls	85	8	7	0·14	3

Table 2. *(continued)*

Horizon	Depth (cm)	Hue	Value/chroma Dry	Value/chroma Moist	Dry consistence	Texture	Sand 2–0·05 mm (%)	Silt 0·05–0·002 mm (%)	Clay < 0·002 mm (%)	Organic C (%)	$CaCO_3$ equiv. < 2 mm (%)
Bk4	65–86	6YR	6/4	4·5/4	sh	ls	85	10	5	0·11	4
Bk5	86–115	6YR	6/4	4·5/4	s	ls	82	12	6	0·10	6

Colours given are the dominant ones; smaller volumes of other colours are present in some horizons. Intermediate hue designations indicate the closest hue; e.g. 6YR indicates that the hue is between 7·5YR and 5YR, but closer to 5YR than 7·5YR. Abbreviations for texture and consistence follow the Soil Survey Staff (1951). Particle size on carbonate-containing basis by method 3Al; organic C by method 6A1c; $CaCO_3$ equivalent by method 6E1g (Soil Survey Investigations Staff, 1991). Tr = trace, either not measurable by quantitative procedure used or less than 0·5%; –indicates analyses run but none detected. Particle size data reported in tens of percent, rounded to whole numbers in this table. The K1b horizon of Cruces 94–1 consists of carbonate-cemented fragments and has no fine earth.

accumulation. This suggests that at an earlier time the soil may have had a much thicker B horizon and an associated horizon of carbonate accumulation.

Branches of the major roots frequently turned downward and grew into cracks in the petrocalcic horizon or into pipes (Fig. 2), as discussed in subsequent sections.

Pipes

Pipes are roughly funnel-shaped, downward extensions of B and/or K horizon materials that commonly contain less carbonate than adjacent horizons (see Gile & Grossman, 1979, p. 185 for a discussion of the origin of pipes). In most soils of La Mesa surface, pipes are in a zone of marked deepening or disappearance of the petrocalcic horizon. An arbitrary depth of at least 1 m to the petrocalcic horizon has been used to denote occurrence of pipes in this report.

The variety of pipes in the study area and their proximity to each other have not been seen previously in numerous exposures of La Mesa soils. Although the cause of this remarkable variety is not known, at least some of it could be associated with local effects of faulting, as could the deep, shattered former petrocalcic horizons (e.g. as at trench 94-4 discussed later).

Soils of pipes have more available soil water than other soils of La Mesa surface because the petrocalcic horizon that is usually adjacent to pipes funnels water into them (Herbel *et al.*, 1994). Thus, pipes are an important source of water for roots.

The Typic Torripsamment, Bluepoint 94-2

The pipe with Bluepoint soils occurs in the south-east corner of the study area (Figs 2 and 3). These soils have about 1% to 10% fine gravel-sized calcrete (carbonate-cemented) fragments throughout. The pipe has no Bt material and in addition there is no silicate clay maximum to suggest accumulation of silicate clay (Table 2). There is evidence of slight carbonate accumulation in the form of stage I coatings on grains. All horizons contain a small amount of carbonate that increases slightly with depth (Table 2). These factors, in materials of middle to early Pleistocene age, indicate that the materials in the pipe have been mixed, probably by rodents. Such mixing of soil materials by soil biota is not uncommon (Gile *et al.*, 1981).

Mesquite roots extend into pedon 94-2 as well as descending along the steeply sloping, in places discontinuous, petrocalcic horizon that forms the edge of the pipe. Mesquite roots descend between some of the tightly fitted prisms below the laminar zone of the petrocalcic horizon. In places, sandy materials of the pipe extend between platy and blocky calcrete fragments, and these places are also exploited by mesquite roots.

At various places along the study trench, sandy materials of the pipe rest on petrocalcic or once-petrocalcic horizons that are now fractured. The study trench cuts across the north side of the pipe, which deepens markedly to the south. For example, the sandy materials in the vicinity of pedon 94-2 are commonly about 1·2 m thick whereas on the south side of the trench the sandy materials are commonly about 1·7 m thick. Also on the south side of trench 94-2, abundant mesquite roots from the coppice dune (Fig. 2) descend into and exploit the sandy materials of the pipe. The sandy materials would facilitate ready and deep penetration of soil moisture for the roots.

Towards the west end of the study trench, sandy materials associated with the pipe gradually thin, and the petrocalcic or near-petrocalcic horizon occurs at the shallower depths that are typical between pipes. In about the western 2 m of the trench are scattered reddish brown zones of Bt material, noncalcareous in part, that on the south side of the trench begin about 0·5 m below the top of the petrocalcic horizon and overlie a deep petrocalcic horizon. As at trench 94-1, discussed previously, these Bt remnants appear to represent a formerly thicker Bt horizon that extended to the top of the deep petrocalcic horizon. The Bt remnants may also represent the Bt horizon of an earlier, larger pipe that has since been largely engulfed by carbonate accumulation in its upper part. In either case, the deep zones of Bt material appear to represent a time of deeper leaching that existed before formation of the upper petrocalcic horizon. The loose material of the pipe is abruptly inset against the Bt material and the contact clearly represents the boundary to rodent activity.

The Typic Haplargid, Sonoita analog 94-3

The pipe with Sonoita analog (Figs 2 and 6; Table 3) extends to at least 2·6 m depth, and thus is considerably deeper than the exposed part of the pipe with Bluepoint soils. The pipe with Sonoita analog has a thick Bt horizon, and in this respect is more similar to most pipes of La Mesa soils than the pipe with Bluepoint soils (Gile *et al.*, 1981). Carbonate contents do not differ greatly from those of the Bluepoint pedon just discussed (Tables 2 and 3). Some horizons are finer-textured than Bluepoint and some are harder (Tables 2 and 3). These factors did not prevent a few fine roots from penetrating the analysed pedon, which was sampled at the tape (Fig. 6). However, roots were most abundant descending along the contact between the pipe and the petrocalcic horizon that encircles it. This is also the route of more abundant soil water as previously discussed. In addition to roots from the excavated dune, roots from mesquite on the west side of trench 94-3 (Fig. 2) also extended down into the pipe and were concentrated along the contact to the petrocalcic horizon.

There is general agreement that climates of the south-west were wetter and cooler during the early Holocene than today (Hall, 1985; Spaulding & Graumlich, 1986; Spaulding, 1991). Laboratory data (Table 3) show two slight, but distinct maxima in both clay and carbonate in the thick Bt horizon. The stage I carbonate extending to 89 cm depth is similar in depth and morphology to the stage I carbonate in soils of Organ age, known to be less than 7 ka old by radiocarbon dating of buried charcoal (Gile *et al.*, 1981). The zone below 89 cm contains stage II nodules and masses in its upper part, and could have formed during this wetter period in the early Holocene, when wetting fronts would have extended to greater depths than now.

The Typic Calciargid, Yucca analog 94-4

The pipe with Yucca analog (Fig. 2) is exposed in two places, in the north wall of trench 94-4 and in the walls of trench 94-1 on its west end. Yucca analog 94-4 contains both more carbonate and more clay than Sonoita analog 94-3 (Table 3), but did not noticeably resist penetration by mesquite roots. Contrary to the usual situation, in Yucca analog 94-4 (Table 3) the Bt material and the argillic horizon underlie the calcic horizon instead of occurring largely or wholly above it.

Beneath the deep argillic horizon and extending all around the trench is a shattered-appearing K horizon with many indurated fragments. The K horizon is broken in so many places that only a few spots qualify as a petrocalcic horizon. Some of the fragments have laminar structure, indicating that stage IV had formed but has since broken.

Preservation of a zone relatively low in carbonate between two carbonate maxima is similar to the low-carbonate zones with Bt material preserved beneath the stage IV horizon at the west end of trench 94-2, except that at 94-4 the overlying carbonate horizon is weak stage III and thus must be much younger. Such preservation of Bt material between two carbonate maxima may be related to the long-continued carbonate and clay accumulation in these ancient soils: as these substances continued to accumulate, the once-deeply penetrating wetting fronts would have been gradually forced upward, possibly aided by a change to drier climates at times during soil

Table 3. *Characteristics of analogs of the Typic Haplargid Sonoita and the Typic Calciargid Yucca*

Horizon	Depth (cm)	Hue	Value/chroma Dry	Value/chroma Moist	Dry consistence	Texture	Sand 2–0·05 mm (%)	Silt 0·05–0·002 mm (%)	Clay <0·002 mm (%)	Organic C (%)	$CaCO_3$ equiv. <2 mm (%)
Sonoita analog 94–3											
A	0–5	6YR	6/4	4·5/4	s	s	88	7	5	0·16	1
BAtk	5–13	5YR	5·5/5	4/5	sh	fsl	79	11	10	0·18	1
Btk1	13–27	5YR	5·5/5	4/5	sh	fsl	79	12	10	0·22	3
Btk2	27–41	5YR	5·5/5	4/5	sh	ls	81	11	9	0·13	2
Btk3	41–61	5YR	6/5	4·5/5	sh,h	ls	83	9	8	0·09	1
Btk4	61–74	5YR	5·5/5	4·5/5	h,vh	ls	82	9	9	0·05	1
Btk5	74–89	5YR	5·5/5	4·5/5	vh	fsl	81	9	11	0·05	1
Btk6	89–112	5YR	6/4	4·5/5	vh	fsl	78	10	13	0·08	4
Btk7	112–131	5YR	6/5	4·5/5	vh	fsl	78	9	13	0·05	1
Btk8	131–154	5YR	5·5/4	4/4	sh	fsl	79	10	11	0·04	4
Btk9	154–170	5YR	6/4	4·5/4	h	ls	81	9	10	0·05	1
Btk10	170–195	5YR	5·5/4	4·5/4	sh,h	ls	82	9	9	0·06	1
BCtk1	195–210	5YR	6/4	4·5/4	sh,h	ls	85	8	7	0·02	1
BCtk2	210–233	5YR	6/4	4·5/4	sh	ls	85	8	7	0·04	1
BCtk3	233–258	5YR	6/4	4·5/4	sh	ls	84	9	7	0·03	–
Yucca analog 94–4											
A	0–4	5YR	5·5/4	4/4	s	ls	81	11	8	0·15	3
BA	4–10	5YR	6/4	4·5/4	s	fsl	76	14	10	0·14	6
Bk1	10–23	5YR	6/4	4·5/4	sh	ls	80	11	9	0·18	4
Bk2	23–40	6YR	6/4	4·5/4	sh,h	fsl	76	15	10	0·13	7
Bk3	40–54	7·5YR	6·5/4	4·5/4	h	fsl	75	16	10	0·13	7
K1	54–66	7·5YR	7/3	5·5/3	vh	fsl	71	17	12	0·13	11
K2	66–81	7·5YR	7/4	5/4	vh	fsl	71	15	14	0·13	14
K3	81–96	6YR	7/4	5·5/4	vh	fsl	73	12	15	0·12	12

Table 3. *(continued)*

Horizon	Depth (cm)	Hue	Value/chroma		Dry consistence	Texture	Sand	Silt	Clay	Organic C (%)	$CaCO_3$ equiv. <2 mm (%)
			Dry	Moist			2–0·05 mm (%)	0·05–0·002 mm (%)	<0·002 mm (%)		
Btk1	96–115	5YR	5·5/4	4/4	vh	fsl	71	9	20	0·08	10
Btk2	115–145	5YR	6/4	4·5/4	vh	fsl	75	9	17	0·06	9

Colours given are the dominant ones; smaller volumes of other colours are present in some horizons. Intermediate hue designations indicate the closest hue; e.g. 6YR indicates that the hue is between 7·5YR and 5YR, but closer to 5YR than 7·5YR. Abbreviations for texture and consistence follow the Soil Survey Staff (1951). Particle size on carbonate-containing basis by method 3Al; organic C by method 6A1c; $CaCO_3$ equivalent by method 6E1g (Soil Survey Investigations Staff, 1991). Tr=trace, either not measurable by quantitative procedure used or less than 0·5%; –indicates analyses run but none detected. Particle size data reported in tens of percent, rounded to whole numbers in this table. The K1b horizon of Cruces 94–1 consists of carbonate-cemented fragments and has no fine earth.

development. In some instances, such upward movement may have been rapid enough that a zone with less carbonate could form between the two carbonate maxima.

Study area in playa

Landscape and vegetation at the playa study area differ markedly from the main study area. There are no dunes and the playa is level. Vegetation is mostly tobosa (*Pleuraphis mutica*), with a few burrograss (*Scleropogon brevifolius*) and mesquite, with scattered barren areas. Soils also differ greatly as discussed in the following section.

The Ustic Haplocalcid Reagan and underlying materials

The soil at the playa site is in the Reagan series (fine-silty, mixed, thermic Ustic Haplocalcids), and has formed in Petts Tank sediments of late Pleistocene age (Gile *et*

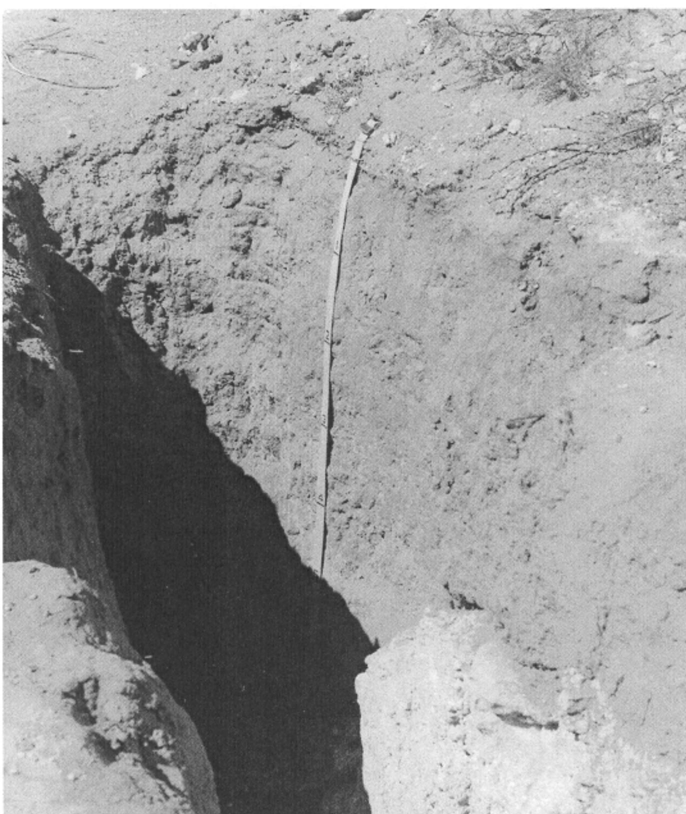

Figure 6. Sonoita analog 94-3 in deep pipe (see text discussion and Table 3). Note the scattered stage II nodules at about 3 to nearly 4 ft depth. A concentration of mesquite roots, not visible from this angle, descends along the steeply sloping boundary between the pipe and the petrocalcic horizon to the right. Soil on the right is overlain by spoil from the trench. Scale is in feet. (Photographed January 1994).

al., 1981). These deposits are high-carbonate sediments derived from sedimentary and igneous rocks of the San Andres Mountains to the east (Fig. 1). Laboratory and morphological data for similar Reagan soils in Petts Tank sediments may be found in Gile & Grossman (1979, pp. 830, 831, 940, 941) and Gile *et al.* (1981, 1995). The distinct prisms of the Reagan soils are important to water movement because cracks form between them when the soil dries, and these cracks are routes for water entry and growth of mesquite roots. Below the Reagan soil, a krotovina in a buried soil is a route for downward movement of both roots and water as discussed later (krotovinas are the fillings of tunnels made by rodents; Soil Survey Division Staff, 1993).

The Reagan soil has a thin A horizon, a Bw (structural) horizon, and a nodular stage III K horizon from about 50 to 95 cm. Carbonate nodules decrease with depth and only a very few occur below a depth of about 130 cm. As is typical of soils in Petts Tank sediments, textures are clayey or very close to it throughout, with abundant silt as well as clay.

The clayey Petts Tank sediments extend to a depth of about 2·2 m. Beneath them are redder (e.g. 5YR 6/4, dry) sandy sediments, commonly stratified, and in places stratified with finer, less red sediments. These stratified sediments rest abruptly on an underlying buried soil, and may mark the beginning of the major erosional–depositional interval associated with the Petts Tank sediments in the late Pleistocene. The reddish sandy layers contain less carbonate than the finer Petts Tank sediments, and may have been locally derived from the nearby soils of La Mesa age, which commonly have 5YR hue in part.

The stratified zone, which extends to a depth of about 3·2 m near the studied root, overlies a buried soil with a nodular stage II B horizon that is underlain by a stage III K horizon. This buried soil may be a playa analog of the basin-floor Jornada I soil observed to the south (e.g. see Gile *et al.*, 1981, pp. 182–188, for data, photographs, and discussion). With depth the stage III horizon grades to horizons with less carbonate, and a thin, soft, loamy layer, mostly noncalcareous, occurs at about 4·2 to 4·4 m depth where it rests on gypsum-containing layers. These layers, some of which are cemented with gypsum, contain little or no carbonate and extend to the bottom of the trench.

The excavated mesquite roots

The root system of a small mesquite plant 60 cm tall and 90 cm in diameter was excavated (Fig. 7). It was growing in a dense stand of tobosa (*Pleuraphis mutica*). Like the dune mesquites, growth rings were poorly defined and age could only be estimated as about 30 years. Continual soaking of the soil led to trench wall instability and so all roots were exposed using ice picks rather than water sprays.

The mesquite plant had a prominent tap root with a beginning diameter of 29 mm which was followed to a depth of 5·5 m (Fig. 7). At this depth it was still 2·9 mm in diameter but was growing horizontally away from the trench so was not followed further. Horizontal, first order roots were fairly well developed in the upper 1 m of soil and extended outward nearly 3 m. Below a depth of 1 m the first order branches grew downward rather than horizontally (Fig. 7). There were very few fine branches on the tap root and first order branches between 1·5 and 3·2 m depths. Below 3·2 m fine roots were much more abundant even though the soil material was still tightly compact. From 4·2 to 5 m depth the tap root travelled downward in a krotovina and there were many fine roots.

At a depth of 70 cm there was an upward-growing second order root, branches of which extended to within 5 cm of the soil surface (Fig. 7). Upward-growing roots were also present on relatively short first order roots close to the base of the plant. The upper 60 cm of soil was occupied by a mass of tobosa roots but the mesquite roots penetrated even very dense clusters of tobosa roots. Tobosa roots did not penetrate deeper than 1·4 m.

Roots of a very small (17 cm tall) mesquite plant which had approximately nine growth rings were excavated at the playa trench. This plant also had a prominent tap root which split into two branches at 1·65 m depth. The branches ended at 2·7 and 3·2 m depths, respectively. There was only one major first order branch arising at 0·65 m depth and growing downward to 2 m depth. It appears that the strategy of mesquite plants in this grass sod situation is to develop deeply penetrating roots first and then to develop horizontal roots in the upper soil layers.

Just south of the Experimental Range, mesquite and other shrubs were not found in clayey Torrerts of a playa that floods at intervals of every year to a few years. Presumably, the occasional flooding would have killed any small shrubs that started to encroach into the playa.

Conclusions

Mesquite is the most numerous shrub involved in invasion of grasslands in a basin floor of southern New Mexico. Although the spread of mesquite seed by cattle has been important (Buffington & Herbel, 1965), a major factor is the adaptability of mesquite roots to a wide variety of soils and soil conditions. A study area with coppice dunes had a complex pattern of Torripsamments, coarse-loamy Petrocalcids, coarse-loamy Calciargids, and sandy Haplargids. Mesquite roots penetrated all of the studied

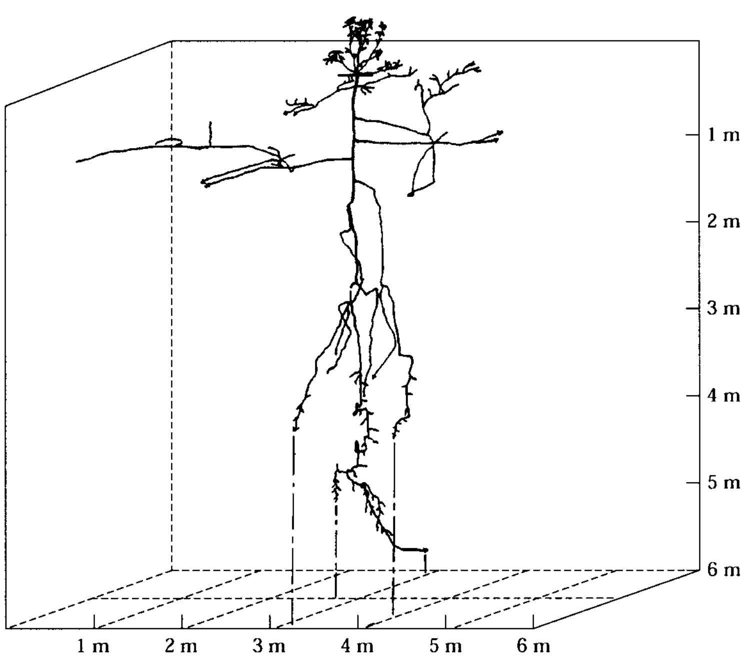

Figure 7. Three-dimensional diagram showing root system of mesquite in the Reagan soil. Arrows denote roots which grew into the trench (located at the front face of the drawing) or were not followed. Similar to the main study area, upward-growing roots extended to within 5 cm of the soil surface, here penetrating a dense tobosa sod. Short horizontal line beneath plant locates the soil surface.

soil horizons except for dense, extremely hard petrocalcic horizons, along which the roots grew and proliferated for many meters, in places extending down cracks and pipes in the petrocalcic horizon. Additionally, the study site in a playa showed mesquite roots in a fine-silty Haplocalcid extending to depths of at least 5·5 m. At both sites, mesquite roots grew upward as well as downward to utilize minor precipitation events that only wet the soil to depths of a few centimeters. Thus, mesquite roots can grow in a wide variety of soils, and extend long distances both laterally and vertically to utilize soil water at all depths.

In numerous root excavations at the Jornada Experimental Range, the mesquite root at 5·5 m depth at the playa study site is the deepest found to date. This is slightly greater than the depth of a crucifixion thorn root (5·2 m) reported in a previous study (Gile *et al.*, 1995). It should be emphasized that these are minimum depths because the roots of both plants were still extending either down or laterally at those depths.

An earlier study (Gile *et al.*, 1995) found that long, gentle rains which occasionally occur in this arid region can locally penetrate to substantial depths by means of present and former root channels, animal burrows, pipes in various stages of development, and cracks that form when the soil dries. The playa study revealed krotovinas to be another means for deep penetration of roots and water, and tends to confirm the interpretation of their local deep penetration as found in the previous study. Krotovinas tend to be softer and more pervious than the surrounding soil, and thus constitute still another long-term route for movement of soil and water to substantial depths.

The ancient soils of La Mesa reflect an extremely long period of soil and landscape stability on the studied part of the basin floor. Land survey notes, grazing history and the abrupt boundary of stratified coppice dune sediments on La Mesa soils show that this long period of stability was abruptly ended by strong wind erosion caused by large-scale introduction of cattle in the 1880s, by subsequent overgrazing, and by the invasion of grassland by shrubs.

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