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Soils and sediments associated with remarkable, deeply-penetrating roots of crucifixion thorn (*Koeberlinia spinosa* Zucc.)

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Root systems of crucifixion thorn (*Koeberlinia spinosa* Zucc.) were excavated on an alluvial-fan toeslope in a desert area of southern New Mexico. High-carbonate toeslope deposits of late Pleistocene age overlie low-carbonate middle Pleistocene deposits of an ancestral Rio Grande. These two deposits and their soils provide markedly different geomorphic, pedogenic, chemical and physical environments for the development of tap roots and their branches. Roots descended through the fan toeslope sediments and penetrated the river deposits to a depth of at least 5·2 m, much deeper than is usual for root penetration in this area. Remarkably, 2nd and 3rd order branches originated at depths of 2·3 to 3·8 m and grew vertically upward, branched profusely in the top 1 m of soil, and extended to within 10 cm of the soil surface. It is believed that occasional deeply penetrating soil water moves down channels once occupied by roots and other openings in the soil, and that this is a source of water for growth of the deeply penetrating roots, as well as for the roots that grow upward.

Keywords: desert soils; buried soils; gypsum hardpan; root morphology; upward-growing roots; deeply penetrating soil water routes

Introduction

The importance of plant root systems in arid environments was recognized at an early date (Cannon, 1911; Markle, 1917). These early studies indicated, at least to some degree, the influence of soil types and sediments on root morphologies. Ludwig (1975), in reviewing adaptations of root systems in desert environments, concluded that root system size and form depends upon the soil environment in which the plant became established. In North American deserts alone, much has been learned about seedling root growth (e.g. Walters & Freeman, 1983; Brock, 1986), root biomass (e.g. Chew & Chew, 1965; Pieper & Herbel, 1982), root productivity (e.g. Caldwell & Camp, 1974), root water relations (e.g. Nobel 1976, 1977; Nobel & Sanderson, 1984; Richards & Caldwell, 1987), root phenology and metabolism (e.g. Eissenstat &

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Caldwell, 1988; Nobel, 1989), and root system interactions and competition (e.g. Fonteyn & Mahall, 1978, 1981; Manning & Barbour, 1988; Mahall & Callaway, 1992). However, the intractability of working with root systems *in situ* has greatly restricted knowledge of even basic morphology of roots of many desert plants which grow in a wide variety of soil–sediment complexes. The objectives of this study were to determine the morphology of the root system of crucifixion thorn (*Koeberlinia spinosa* Zucc.), to characterize the soils and sediments in which it was growing, and to relate the root system to soil characteristics.

Study site

The study site is on the Jornada Experimental Range, in the basin and range country of southern New Mexico (Fig. 1). The site slopes 1/2% to the west and is on the toeslopes of an alluvial-fan piedmont, near the eastern edge of a broad basin floor. The site has major physiographical and parent material significance because it contains both high-carbonate toeslope sediments derived from the San Andres Mountains and underlying low-carbonate basin-floor sediments deposited by an ancestral Rio Grande. ('High-carbonate' designates parent materials with more than about 15% $CaCO_3$ equivalent; 'low-carbonate' designates parent materials with less than about 2% $CaCO_3$ equivalent.) Westward, the toeslope sediments thin and grade out, slope changes to level or nearly level, and the ancient Rio Grande sediments emerge at the surface. Elevation is 1315 m; depth to the water table is 45 m.

Long-term (1915–92) precipitation at the Range Headquarters (Fig. 1) averages 247 mm annually and 52% of this occurs between 1 July and 30 September. The soils are mostly dry for long periods in the late spring and early summer. Summers are hot; winters are mild. The mean annual temperature is 15°C.

Vegetation on the study site is dominated by tarbush (*Flourensia cernua* DC.) and burrograss (*Scleropogon brevifolius* Phil.). Crucifixion thorn occurs as scattered individuals. Both tarbush and crucifixion thorn have probably become established on the site since 1900 because this is one of the areas of extensive shrub invasion of former grasslands (Buffington & Herbel, 1965).

Materials and methods

A backhoe was used to excavate a 3-m deep trench about 1·5 m from the base of a large, single-stemmed crucifixion thorn. Water was piped to the site from a stockwater pipeline. Water pressure was moderate but sufficient to allow fairly rapid removal of soil from the trench face using a spray nozzle. Water spray and icepicks were used to expose roots to a depth of about 3 m. However, it was found that continual soaking of the soil led to sluffing of the trench walls so the use of water was discontinued for safety reasons. Excavation below 3 m was accomplished with shovels and roots exposed with icepicks.

Vertical maps of exposed roots were made on graph paper at a scale of 10 cm = 2·5 cm. In addition, a base line running through the plant base and parallel to the trench was established and marked at 1 m intervals. Horizontal position of exposed roots was recorded at a scale of 1 m = 5 cm. Using the vertical and horizontal maps it was possible to construct 3-dimensional drawings of the root system.

A similar trench was excavated by a cluster of small crucifixion thorn plants about 65 m to the east of the first trench. Water was used to excavate roots at this site because roots did not penetrate an extremely hard layer at a depth of 3·3 m. At both sites the trenches were oriented so that root systems of species other than crucifixion thorn could be excavated. Root diameters were measured with vernier calipers to the nearest

0·1 mm. The heartwood of the crucifixion thorn stems was filled with dark brown deposits and growth rings were not discernable even after polishing so no estimate of plant age could be made.

The trench at the first study site was deep enough (5 m) that substantial thicknesses of both the fan toeslope and underlying river sediments were exposed. The studied pedon adjacent to the root was sampled by horizons to a depth of 498 cm. Horizon designations follow Guthrie & Witty (1982) except for the K horizon nomenclature (Gile *et al.*, 1966) and for the designations for buried soils, which are placed at the end of the designation to handle pedons with more than one buried soil. Laboratory analyses were done by the National Soil Survey Center, USDA-SCS, in Lincoln, Nebraska (Table 1).

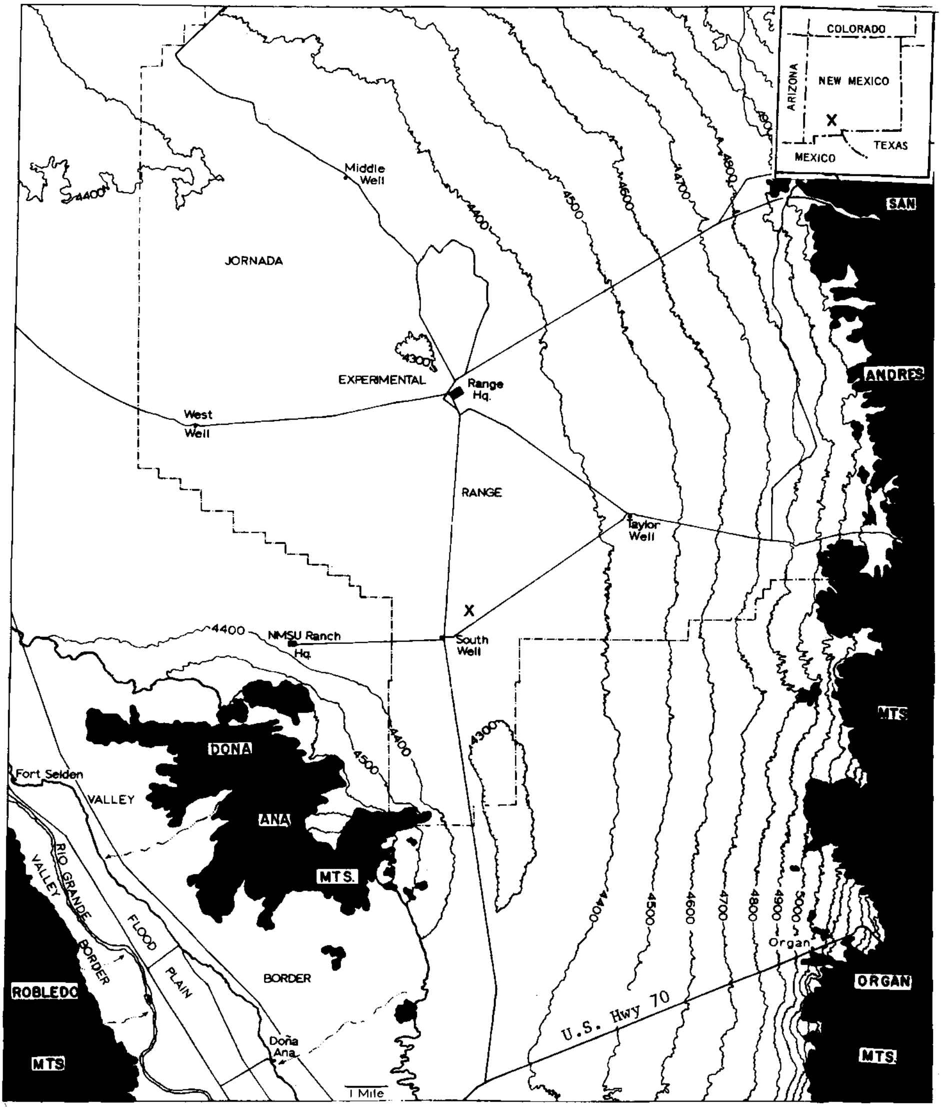

Figure 1. Major physiographic features in the vicinity of the study area (located by ×, north-east of South Well). The Rio Grande Valley is at lower left. Location in New Mexico is shown by the inset map at upper right. Contour intervals are in feet.

Table 1. *Characteristics of an Ustollic Calciorthid and underlying materials. Colors given are the dominant ones; smaller volumes of other colors 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*

Horizon		Hue	Value/ chroma		Structure	Dry Consis- tency	Tex- ture	Particle-size distribution (mm)								Organic C	$CaCO_3$ equiv. mm		Gyp- sum	E.C.
			Dry	Moist				Sand fractions					Sand	Silt	Clay					
								2–1	1– 0·5	0·5– 0·25	0·25– 0·1	0·1– 0·05	2– 0·05	0·05– 0·002	< 0·002		<2	<0·002		
	cm					Ustollic Calciorthid in Petts Tank sediments (late Pleistocene)									%					
A	0– 6	7·5YR	7/2	5/3	2f,mpl	s,sh	sicl		1	5	11	22	40	41	19	0·75	14	5	—	0·84
Bw	6–21	7·5YR	7/2	5/3	1fpr- 2f,msbk	h	cl		1	4	9	11	25	36	39	0·70	30	15	tr	1·71
K21	21–35	7·5YR	7·5/2	5·5/3	1fpr- 2f,msbk	h	sic		1	4	6	8	18	41	41	0·57	46	20	—	0·91
K22	35–51	7·5YR	8/2	6/3	1fpr- 2f,msbk	h,vh	sic			2	3	7	13	47	40	0·40	45	19	—	0·87
K31	51–64	7·5YR	7/3	6/3	1fpr- 2f,msbk	h,vh	sic		1	3	5	9	17	43	40	0·28	38	16	—	0·86
K32	64–81	7·5YR	7/3	5/3	2mpr- 2f,msbk	h,vh	c		1	4	6	9	21	39	41	0·21	36	16	—	1·01
Bk1	81–93	7YR	7/3	5·5/3	2mpr- 2f,msbk	h,vh	sic		1	5	10	11	27	33	39	0·16	31	14	—	1·18
Bk2	93–108	6YR	6·5/3	5/3	2mpr- 2f,msbk	vh	sic			2	5	5	13	40	48	0·16	41	18	—	1·97
Bk3	108–124	6YR	6·5/3·5	5/3·5	2mpr- 2f,msbk	vh	c		1	3	5	8	17	38	46	0·15	35	15	—	3·15
Bk4	124–138	7·5YR	7/3	5/3·5	2mpr- 2f,msbk	vh	sic			2	2	5	9	42	49	0·16	39	16	—	7·35
Bw1	138–155	6YR	6/3	5/3·5	2mpr- 2f,msbk	vh	cl			1	7	17	26	36	38	0·11	28	11	—	9·32
Bw2	155–170	6YR	6·5/3	5/3·5	2mpr- 2f,msbk	vh	cl		1	4	9	20	32	33	35	0·11	23	9	—	9·74

(continued)

Table 1. *Continued*

Horizon		Hue	Value/ chroma		Structure	Dry Consis- tency	Tex- ture	Particle-size distribution (mm)								Organic C	CaCO$_3$ equiv. mm		Gyp- sum	E.C.
								Sand fractions					Sand	Silt	Clay					
			Dry	Moist				2–1	1–0·5	0·5–0·25	0·25–0·1	0·1–0·05	2–0·05	0·05–0·002	< 0·002		<2	<0·002		
	cm		Buried Typic Haplargid in the upper Camp Rice Formation (fluvial facies; middle Pleistocene)													%				
								Btb horizon and underlying hardpan												
2BAtb	170–179	5YR	6·5/3	5/4	1msbk	vh	scl		2	13	26	21	62	16	22	0·05	11	5	—	6·59
2BAtkb	179–195	6YR	6·5/3	5/3·5	1msbk	vh	fsl		2	15	27	21	65	17	18	0·06	9	4	—	1·35
2Btb	195–203	5YR	6/3	5/3	1msbk	h	fsl	1	3	16	28	18	66	16	18	0·05	9	4	—	4·03
2Bk1b	203–227	7·5YR	7/3	5/4	1msbk	h·vh	cl		2	7	16	13	38	32	30	0·08	20	9	tr	3·33
2Bk2b	227–258	7·5YR	8/3	6/3	1msbk	vh	fsl	1	4	10	19	18	52	46	2	0·03	4	1	27	4·52
2Bk3b	258–277	10YR	8/2	5·5/2	1msbk	vh	fsl		5	9	13	27	54	43	3	0·03	4		25	8·05
								Layers with abundant fine and very fine sand and gypsum												
2C1b	277–294	10YR	8/2	6/2	1msbk	h,vh	vfsl		3	7	18	29	57	40	4	0·02	1	1	22	9·15
2C2b	294–316	10YR	8/2	6/2	1msbk	sh,h,vh	vfsl		2	5	36	28	70	25	5	0·02	1	1	18	9·85
2C3b	316–348	10YR	8/2	6·5/2	1msbk	sh,h,vh	vfsl		2	5	32	32	70	24	5	0·03	2		15	4·85
2C4b	348–379	10YR	8/2	6/2	1f,msbk	sh,vh	vfsl		1	3	14	46	64	33	3	0·01	tr		8	3·85
								Layers with abundant silt and gypsum												
2C5b	379–398	10YR	8/2	6·5/3	1msbk	vh	sil	1	4	4	5	17	30	66	4	0·01	tr		20	7·17
2C6b	398–423	10YR	8/2	6/2	1msbk	vh	sil			1	6	32	38	58	4	0·02	—		2	11·20
2C7b	423–439	10YR	7·5/3	6/3	1msbk	vh	sil	tr	2	3	2	12	18	69	13	0·02	tr		10	11·40
2C8b	439–446	10YR	7·5/3	5·5/3	1f,msbk	vh	sl	1	2	3		8	14	84	2	0·01	tr		12	13·10
2C9b	446–469	10YR	7·5/3	5·5/3	1msbk	vh	l	2	7	14	8	6	36	43	20	0·03			3	19·50
2C10b	469–475	10YR	8/3	6/3	1msbk	vh	l	2	8	17	11	6	44	37	20	0·03	tr		2	19·30
								Sand at base												
2C11b	475–498	7·5YR	7/3	5/2	m,sg	s,l	cos	8	27	47	12	1	95	2	3	tr	tr			2·16

Abbreviations for structure, consistence and texture follow the Soil Survey Staff (1951). Particle size on carbonate-containing basis by method 3A1; organic C by method 6A1c; CaCO$_3$ equivalent by method 6E1g; gypsum by method 6F1a; and electrical conductivity by method 8A3a (Soil Survey Investigation Staff, 1991). — indicates analysis run but none detected. tr=trace, either not measurable by quantitative procedure used or less than reportable amount. Particle size data reported in tenths of percent, rounded to whole numbers in this table. Values less than 0·5% are blank.

Results

Roots of a large crucifixion thorn plant

The top of the large crucifixion thorn plant had a height of 1·5 m and a diameter of 2·5 m. The prominent taproot was about 10 cm in diameter at the top but tapered rapidly and was only 3·1 cm in diameter at 1·73 m. The tap root was followed to a depth of 3·64 m at which point it made a loop and turned away from the trench. At a depth of 3·25 m the tap root was constricted to a diameter of 0·84 cm as it penetrated a hard soil layer (Table 1), but it regained diameter and was about 1·5 cm in diameter when it turned away from the trench.

The first remarkable feature of this root system was the absence of lateral branches on the upper portion of the taproot (Figs 2, 3). A major 1st order branch originated at 1·78 m depth and a second at a depth of 2·1 m (Figs 2, 4). The roots were contorted and seldom round in cross-section after the first divisions. For example, the upper 1st order branch had dimensions of 2·40 × 1·64 cm.

The second remarkable feature of the root system was the roots that grew vertically upwards. The upper 1st order branch gave rise to a 2nd order root at 3·55 m depth which grew upward for 2·6 m before branching (Figs 2, 5). This root had a diameter of about 1·65 cm. At a depth of about 0·98 m a 3rd order branch arose which also grew upward. Branching was fairly diffuse above a depth of 0·8 m and most of the branches had an upward or horizontal orientation (Fig. 2). Some 4th through 6th order branches with diameters ranging from 0·35 cm to 0·14 cm were traced to within 10 cm of the soil surface. Following the finer branches was not easy because the upper 1 m of soil was also occupied by burrograss roots. The 2nd order root reached a depth of 0·35 m (diameter 1 cm) where it turned and grew horizontally but was lost when a portion of the trench wall caved in. Other 2nd or 3rd order roots with diameters ranging from 0·7 to 0·9 cm grew vertically or obliquely upwards from depths of 2·3 to 3·8 m (Fig. 2). There was a striking absence of branches on the vertical roots until they reached about 1 m depth.

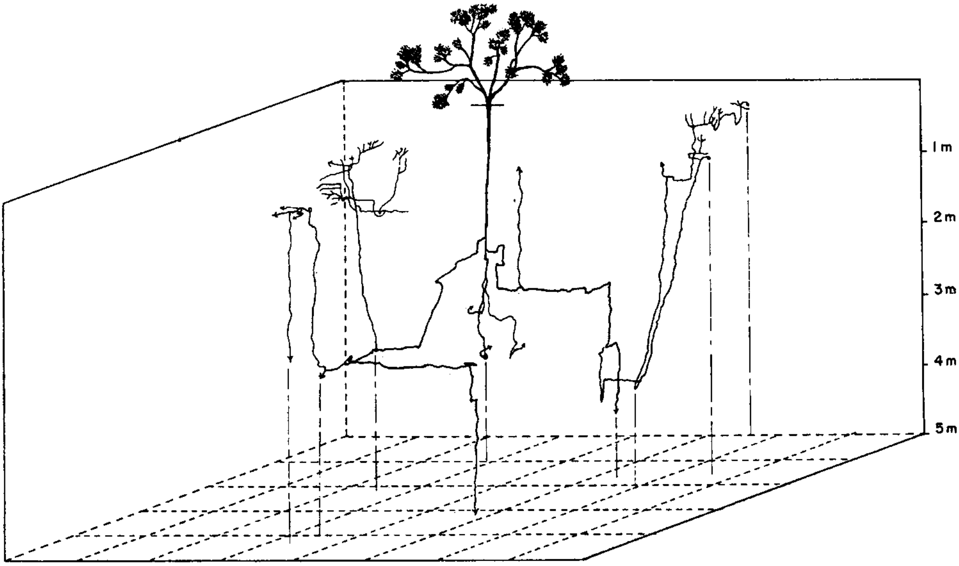

Figure 2. Root system of a large crucifixion thorn plant. Vertically ascending roots had branches which extended to within 10 cm of the soil surface. The deepest downward growing root had a diameter of 1·85 cm at a depth of 5·2 m.

A third remarkable feature of this root system was its great depth of penetration, which was assisted by its ability to grow along the top of very compact layers until a less compact zone was found for descent. The upper 1st order branch was roughly horizontal for a short distance, then descended almost vertically to a depth of about 210 cm (Figs 2, 3 and 4). After several turns the branch dipped downward until it struck the upper part of a hardpan (at the bottom of the tape, Figs 3, 4) discussed later. About 35 cm further along the top of the hardpan, the branch descended vertically through a less compact part of the hardpan, thence to a root-turning layer at a depth of about 3·5 m. The root-turning layer is a very hard, tight layer that has a particularly high percentage of very fine sand (Table 1). After growing along the top of this layer,

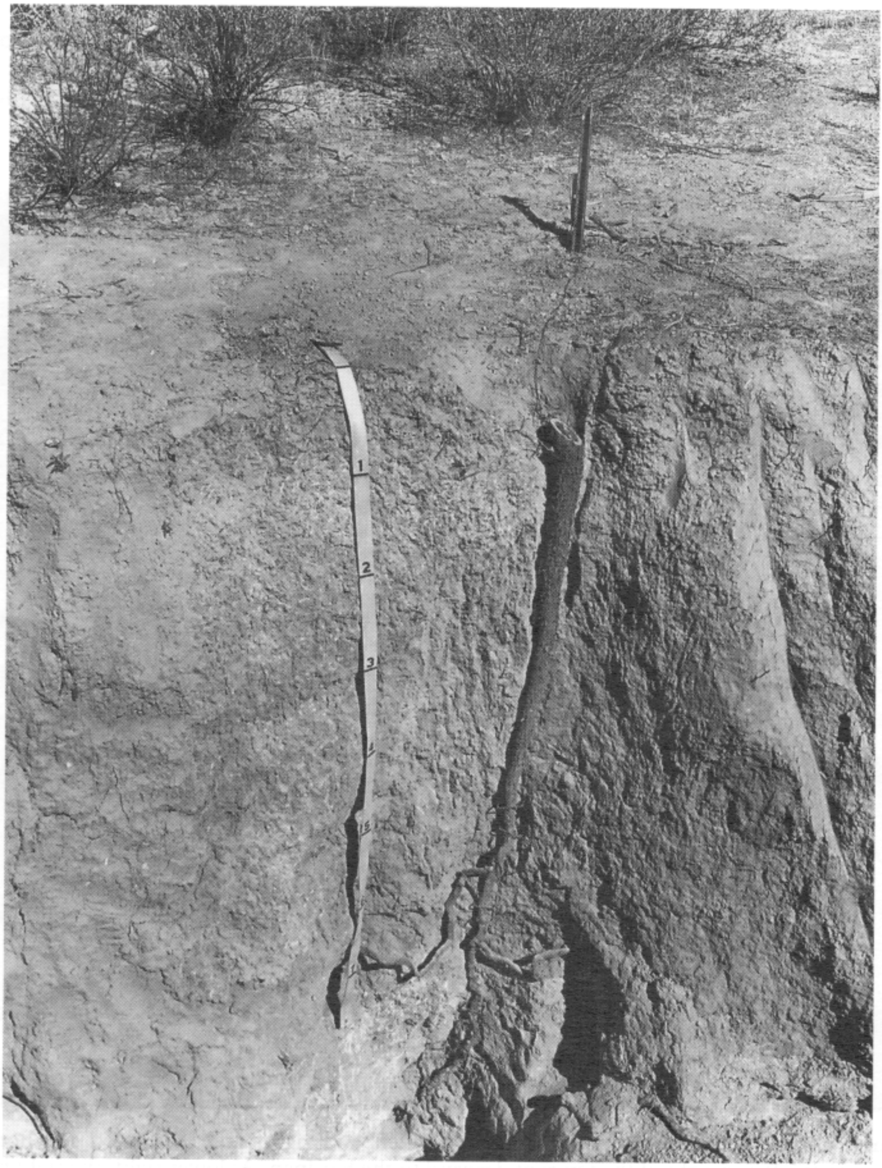

Figure 3. The study site, tap root and branch roots of the large crucifixion thorn (see Fig. 4). Scale is in feet.

the branch found a less compact zone and descended through it into sand at a depth of 4·7 m (Table 1). Sluffing of the sand prevented following the root below a depth of 5·2 m. The root had a round cross-section in the sand and was 1·85 cm in diameter. A few small branches were found between 3·5 and 5 m depth. These were < 0·1 cm in diameter and from 5 to 10 cm in length.

Although about 28 m^3 of soil were excavated in following the roots depicted in Fig. 2, the maximum horizontal extension of the root system was not determined. It was greater than 3·5 m from the base of the plant. Roots of tarbush and burrograss penetrated to about 3 and 1 m depths, respectively.

Roots of small crucifixion thorn plants

At the second excavation site, the roots of two relatively small crucifixion thorn plants in a cluster of small plants were excavated. One plant was 35 cm tall and 25 cm in diameter, the other 56 cm tall and 70 cm in diameter. Although Cannon (1911) found

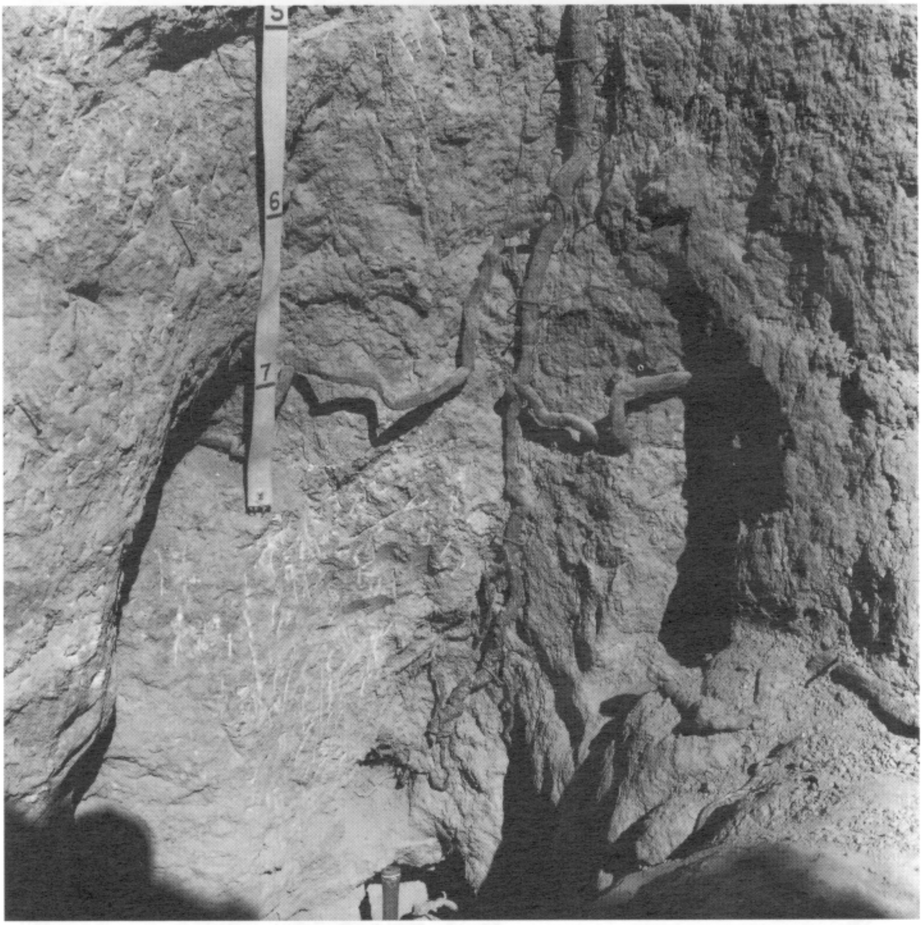

Figure 4. The tap root, its upper branches at left and right, and associated soil horizons. Branches at left and right of the tap root descend to the hardpan. At lower right, the right branch rests on loose material on top of the hardpan (see also Fig. 3). The tap root descends vertically through one of the softer parts of the hardpan. Scale is in feet (30·48 cm).

that crucifixion thorn often grows in clumps which arise from adventitious sprouting, no connections were found between the plants excavated. It is quite possible that connecting roots had decayed.

Both plants had well-developed tap roots (Fig. 6). The tap root of the smallest plant was 1·6 cm in diameter tapering to 0·46 cm at 1 m depth. Two of the three primary tap root branches of the smallest plant were followed to 3·3 m depth where they branched on top of an extremely hard gypsum layer. The tap root of the larger plant was 5·4 cm in diameter but only 2·9 cm in diameter at 45 cm depth where the first 1st order branch originated. This branch grew away from the trench and was not followed. The tap root was 1·9 cm in diameter at 1·3 m depth where two major 1st order branches originated (one of these was dead). The tap root of the larger plant penetrated to 3·2 m depth and grew horizontally on top of the hard layer before turning and growing vertically upward (Fig. 6). The upper portion of this root had been destroyed when the trench was dug. The living 1st order branch arising at 1·3 m depth grew horizontally for about 1·7 m before turning and growing upward (Fig. 6). Branches from this root were followed to within 10 cm of the soil surface in areas

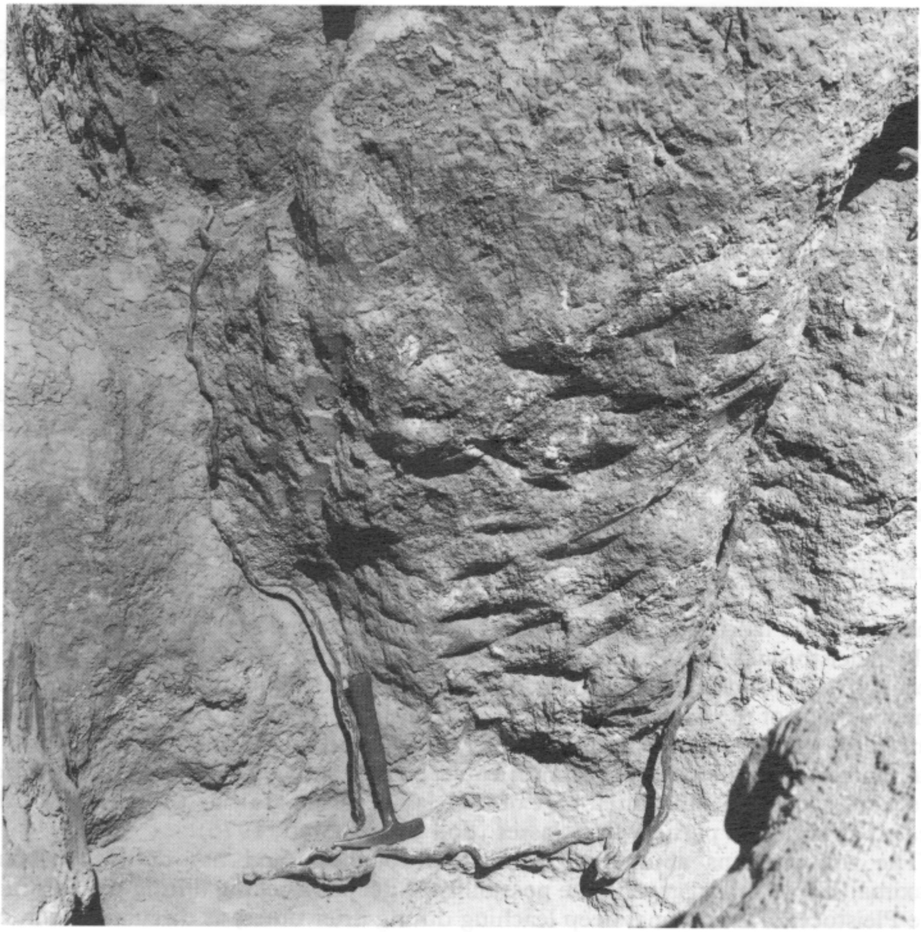

Figure 5. After descending vertically through softer materials, the left branch (Figs 3, 4) extends horizontally along the top of a very hard layer with abundant very fine sand (see text discussion). The hammer gives scale and marks the point at which the 2nd order branch extends upward towards the soil surface.

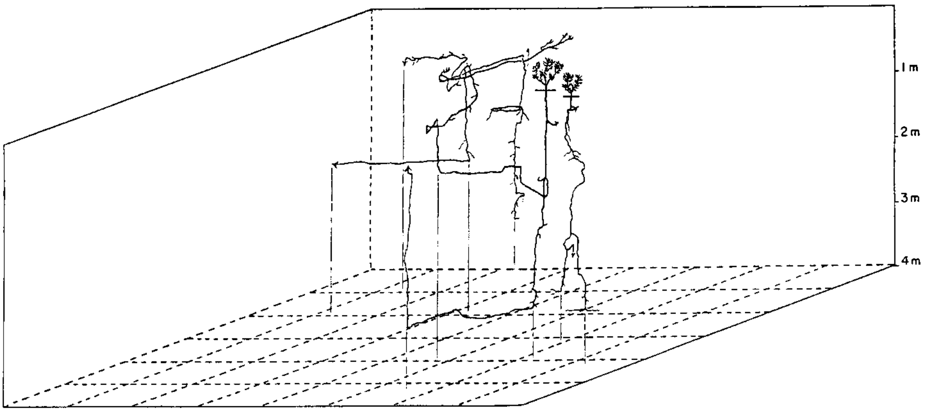

Figure 6. Root systems of two small crucifixion thorn plants. A very compact layer of gypsum at 3·3 m prevented deeper penetration of roots. Roots growing upward extended to within 10 cm of soil surface.

covered by burrograss sod. Other branches were followed downward to the hard layer at 3·3 m depth. The hard layer was penetrated with a jackhammer but no evidence of roots was found below the layer. Maximum horizontal extent of the roots of the largest plant exceeded 5 m.

The small crucifixion thorn plants differed from the large plant in that there were branches originating from the tap roots in the upper 2 m of soil. However, the larger of the small plants had roots which grew upward after encountering compact soil layers just like the large plant at the first excavation (Figs 2, 6).

The studied pedon

For purposes of discussion the thick pedon adjacent to the root (Fig. 3) is divided into the land-surface soil, which has formed in the fan-toeslope deposits (Petts Tank sediments, Gile *et al.*, 1981), and the underlying buried soil and deposits of the ancestral Rio Grande (the upper Camp Rice Formation, fluvial facies; Strain, 1966; Hawley, 1975). Table 1 gives morphological and laboratory data.

Petts Tank sediments and the land surface soil

The soil at the land surface (Figs 3, 7; Table 1) has formed in Petts Tank sediments of late Pleistocene age (Gile *et al.*, 1981), and extends from 0–170 cm depth (Table 1). The soil has formed in high-carbonate sediments derived from sedimentary and igneous rocks of the San Andres Mountains upslope. The soil is in the Reagan series (fine-silty, mixed, thermic Ustollic Calciorthids). Although this soil averages more than 35% clay in the control section (Table 1), it is actually in the fine-silty particle-size class because a substantial part of the clay is carbonate clay (Table 1), which is treated as silt in all particle-size classes (Soil Survey Staff, 1975).

The soil contains abundant carbonate throughout and has double carbonate maxima (Table 1), suggesting the possibility of deeper leaching during pluvials in the late Pleistocene. Occasional deep leaching during drier times, as discussed later, may also have contributed to the lower carbonate maximum. The soil contains no gypsum, and soluble salts are low except for deeper horizons (Table 1). A distinct accumulation of organic carbon occurs in upper horizons, and generally decreases regularly with depth (Table 1).

Upper Camp Rice Formation (fluvial facies)

The buried Bt horizon and underlying hardpan. This zone extends from 170–277 cm depth. Beneath the toeslope sediments and the Reagan soil, the percentage of sand nearly doubles and the percentages of silt, clay and carbonate decrease considerably (Table 1). This prominent change marks the shift from the high-carbonate toeslope sediments to the low-carbonate deposits of the ancestral Rio Grande. The buried Bt horizon in the upper part of the river sediments has a characteristic fabric (termed Bt material, Gile *et al.*, 1981) of Bt horizons in this arid region. Dominant texture of the Bt horizon around the study trench is fine sandy loam, in places grading to a light sandy clay loam. The Bt horizon has more carbonate (in the form of filaments and grain coatings) in upper subhorizons than below (Table 1), probably the result of carbonate descending from the overlying high-carbonate toeslope deposits.

Beneath the Bt horizon is a discontinuous hardpan that extends from 227–277 cm depth. The hardpan is in the upper part of the thick zone of gypsum accumulation, and contains the maximum gypsum in this zone (Table 1). The hardpan also contains some carbonate and soluble salts, as well as substantially more silt and sand, and much less clay than overlying horizons. All of these factors are thought to have contributed to the hardness of the pan. In places, the pan contains reddish, more clayey parts that are not as hard. The tap root descended through one of these softer parts (Fig. 4).

Figure 7. Landscape in the vicinity of the study site. Spoil of the main trench is at right. Spoil from the second study trench is in the middle ground at left. Vegetation in the foreground is tarbush and burrograss. The San Andres Mountains are on the skyline.

Layers with abundant fine and very fine sand and gypsum. This zone extends from 277–379 cm depth and contains abundant fine and very fine sand as well as some gypsum. The gypsum occurs mainly as discrete crystals and nests of crystals, commonly more or less mixed with the fine earth. The bulk of this zone is non-calcareous. Old root channel fillings and remains of roots are common just below the pan. These root features are quite obvious where the sands are soft because they tend to slump, thus exposing the root features. Cemented fillings of root channels are non-calcareous and apparently cemented by gypsum and/or other salts. Presumably, these cemented, non-calcareous fillings formed during an early period of development of the buried soil, before little or any carbonate accumulated in it, and before deposition of the high-carbonate toeslope sediments. Younger, uncemented root channel fillings and channels with root remains are calcareous; these probably formed after carbonate began to accumulate in the buried soil, and/or after deposition of the toeslope sediments.

Layers with abundant silt and gypsum. This zone extends from 379–475 cm depth. Roughly horizontal bands of gypsum are common and range from about 1 to 5 cm thick. The bands are associated with layers that contain abundant silt (Table 1). These finer layers would tend to slow the movement of ground water, thus expediting precipitation of gypsum. The gypsum is thought to have accumulated while ground water was still near the land surface, after the river sediments were deposited but before entrenchment of the Rio Grande Valley to the west (Fig. 1). Some of the bedrock in the San Andres Mountains contains abundant gypsum, and this is thought to have been a major source of the gypsum in the river sediments.

Sand at the base of the study trench. The lowest horizon sampled extends from 475–498 cm and contains abundant medium and coarse sand, with some fine gravel. This layer is distinctly softer and coarser then the overlying material and 'belled out' by falling in at the bottom of the trench (see Fig. 4). These sediments are generally non-calcareous, with only a few calcareous zones.

Observations of soils at the second study site

General stratigraphy at the second site was the same as exposed by the first excavation — a Reagan soil in toeslope sediments overlying a buried soil in ancient sediments of the Rio Grande. This site differed from the first in having a much harder root-turning layer of gypsum at a depth of 3·3 m.

Discussion

A source of water for growth of these deep roots and their upward extension towards the surface is a matter of considerable interest and significance in this arid region because moisture is scarce and seldom penetrates deeply. Studies have shown that roots usually extend only a few millimeters into dry soils (Hunter & Kelley, 1946; Portas & Taylor, 1976). Hydraulic lift of water from deep roots and discharge into upper soil layers for later resorption have been demonstrated for a few species (Caldwell & Richards, 1989; Wan *et al.*, 1993). It is not entirely inconceivable that a plant could, by pumping water out of a root, extend into dry environments. However, we do not feel that such a method of root growth was employed by crucifixion thorn.

An explanation of how moisture reaches these roots may involve a combination of soil morphology (particularly evidence of former openings, and present openings that would allow a preferential route for movement of moisture deep into the soil); the wet–dry climatic cycle and its effect on soils (causing a pattern of repetitive swelling and shrinking of the soils as they wet and dry respectively); and occasional very deep wetting.

The deep extension of cemented and uncemented root channel fillings, channels with no root remains, and channels partly filled with root remains all indicate that vertical channels once occupied by roots are major, long-term conduits for localized water penetration deep into the soil. Other routes for localized deep penetration of soil water are pipes in various stages of development (Gile *et al.*, 1981), animal burrows, and cracks that form when the soil dries (e.g. between prisms). The latter is particularly the case for the Ustollic Calciorthid in which the root began its development; nearly all its horizons have prismatic structure (Table 1).

A pattern of occasional very deep wettings appears to exist at present. The summer rains are commonly high-intensity rains associated with thunderstorms and lead to substantial runoff. In contrast, winter rains tend to be gentler and to have much less runoff. In December, 1991, a record 89 mm of rain fell at South Well, near the study area (Jornada Experimental Range, unpublished information; Fig. 1). The rainfall occurred as rather gentle rains spread over several days, allowing deep infiltration. Observations in trenches and by auger after these rains showed soils with only slightly less clay (than the Calciorthid of this study) wetted to depths of as much as 1·2 m. Thus, water movement down channels formerly occupied by roots, cracks, and other openings in the soil could at times be considerably greater than 1·2 m. Examination of precipitation records at South Well, Jornada Experimental Range Headquarters and nearby Las Cruces (Jornada Experimental Range, unpublished information; Agricultural Experiment Station, 1988) showed that substantial precipitation also occurred occasionally in the winter months before 1991.

Upward growth of the 2nd order branch may also be explained by isolated zones of deep water penetration. Apparently, the left (1st order) branch (Figs 3–5) grew laterally along the 348–379 cm horizon until the branch encountered such a zone, then initiated a 2nd order branch that followed the moisture to the surface.

Deeply penetrating roots may facilitate deep water penetration because after the surrounding materials dry there would be shrinkage away from the root and an opening for water penetration. Deepest water movement would tend to follow the root downward and extend below it, thus forming a tongue of wetted soil below the root that would stimulate further downward growth.

Although roots of shrub species have been found to grow upslope on hillsides (Cannon, 1911; Hellmers *et al.*, 1955; Herwitz & Olsvig-Whittaker, 1989) the vertical ascent of crucifixion thorn roots for 2 m or more appears to be unique. Cannon (1911) partially excavated several crucifixion thorn root systems without finding vertically growing roots but he felt the tap roots probably penetrated to a permanent water table because they were growing on the edge of a flood plain. It is hypothesized that the vertically growing roots are highly hydrotropic and that this easily overrides positive geotropism. The vertically growing roots are probably initiated when a deep wetting zone encounters an existing root and a newly initiated root follows the wetting zone upward. Once in the more frequently wetted upper soil layers the roots branch and are in an ideal position to harvest water from relatively small but more frequent rainfall events. It is interesting to note that in every case where crucifixion thorn roots were found close to the surface they were in burrograss sod where infiltration rates would be higher than in nearby barren areas.

Conclusions

Morphology of crucifixion thorn roots is strongly influenced by characteristics of the soil in which they grow. The roots exhibit an amazing ability to extend along the top of very compact layers in search of a less compact zone for descent to great depths. The roots also have an ability to override geotropism and grow upward for long distances which allows branches to develop close to the soil surface where water can be obtained from small but relatively frequent rainfall events. Occasional large rainfall events make water available for deep penetration along channels once occupied by roots, cracks that form when the soil dries, and other soil openings. Because these factors provide a water supply for both downward- and upward-extending roots of crucifixion thorn, this plant has a root system that can fully exploit rainfall inputs to the soil.

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