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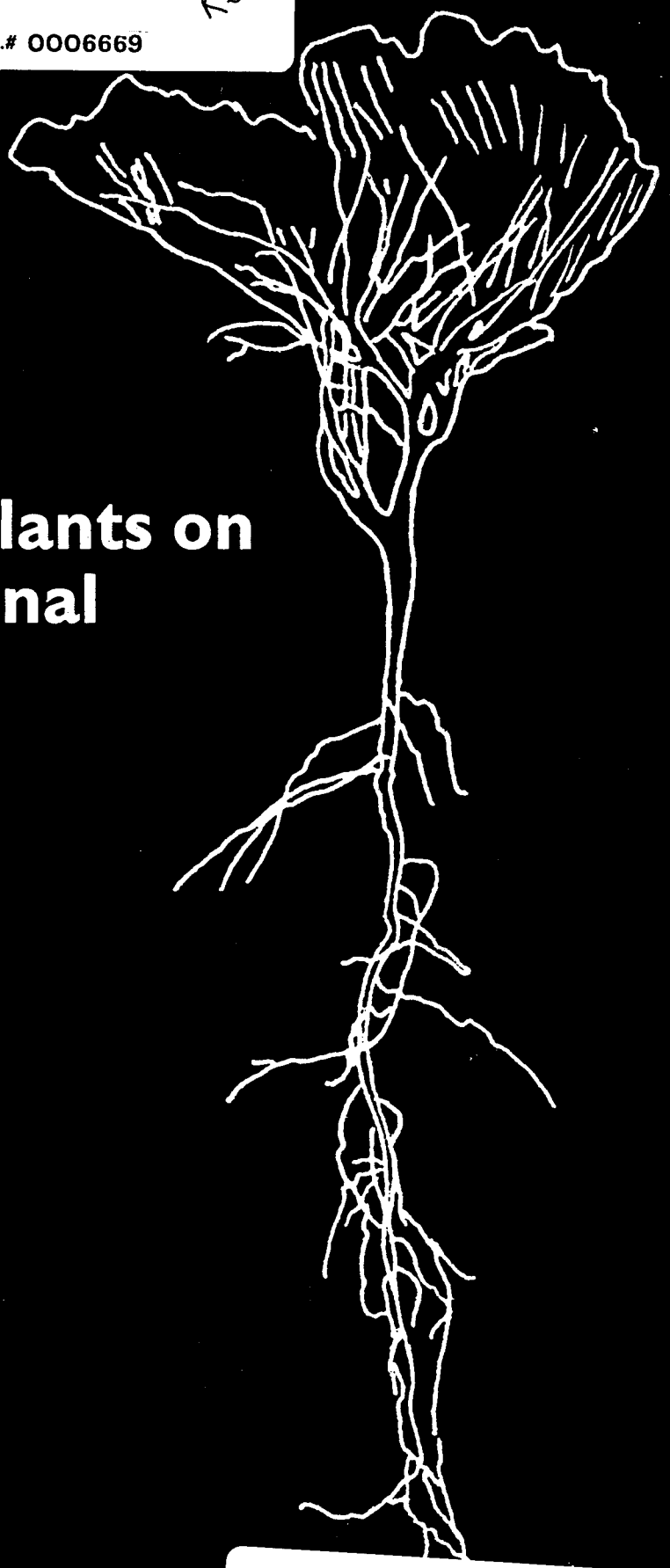

Root Lengths of Plants on Los Alamos National Laboratory Lands

Los Alamos
Los Alamos National Laboratory
Los Alamos, New Mexico 87545

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Gail D. Tierney
Teralene S. Foxx

Drawings by
Dorothy Hoard and Teralene S. Foxx

Los Alamos
Los Alamos National Laboratory
Los Alamos, New Mexico 87545

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ROOT LENGTHS OF PLANTS ON LOS ALAMOS NATIONAL LABORATORY LANDS

by

Gail D. Tierney and Teralene S. Foxx

ABSTRACT

Maximum root lengths of 22 plant species occurring on Los Alamos National Laboratory lands were measured. An average of two longest roots from each species were dug up and their lengths, typical shapes, and qualitative morphologics were noted along with the overstory dimensions of the plant individual with which the roots were associated. Maximum root lengths were compared with overstory (height times width) dimensions. Among the life forms studied, the shrubs tend to show the longest roots in relation to overstory size. Forbs show the shortest roots in relation to overstory size. Measurements of tree roots suggest only that immature trees on the Pajarito Plateau may have root-length to overstory-size ratios near one.

I. INTRODUCTION

This study provides some limited, quantitative information on the root morphology and root depth characteristics of some common southwestern plants that are represented in the local vegetation. The information is used to make estimates of maximum depth of root penetration and to infer a crude relationship between overstory size and maximum root lengths among the native plant species of the Pajarito Plateau.

The interest in root penetration stemmed from two sources. The first was the proposed Nuclear Regulatory Commission standards for disposal of low-level nuclear waste (NRC 1982). These standards require operational procedures that will ban intrusion or disruption for at least 500 years without the need for institutional monitoring and maintenance of the disposal site after 100 years. The second source was the proposed Environmental Protection Agency standards for remedial action at inactive uranium processing sites (EPA 1983). These standards, which are now in effect, would ensure that barriers on mill tailings would effectively minimize the potential hazards with active maintenance for 100 years, at least 200 years without maintenance, and for 1000 years when reasonably achievable. One practical implication of these standards is that a substantial earth cover will be required on near-surface-disposal sites to prevent disruption by natural erosion or anthropogenic cause during the at-least-200-to-500-year epoch. However, one natural means by which even a substantial earth cover could be penetrated is by the roots of native and introduced plants; in fact, investigations into the control and isolation of waste burials have shown that deep-rooted plants may provide a significant pathway for the release of buried toxic materials into the biosphere (Dahlman et al. 1965, Whicker 1976). The possibility of intrusion by deeply rooted plants must be assessed in terms of the evolving successional patterns following disturbance of the site. Potential successional patterns can be predicted only on the basis of site-specific information regarding present species composition, inferred climax species composition, and species morphology. Root morphology and size characteristic of species determine what may succeed on sites disturbed by the burial of toxic wastes.

For the most part, data obtained from this study are not a direct indication of the extent of rooting on disturbed areas such as waste sites. Unless otherwise indicated, root lengths obtained from this study were from plants growing at sites that have not been severely disturbed by man for at least 44 years (the age of the Laboratory as of this writing). Before that, there was

probably only shallow disturbance by grazing or dryland farming.

What this study indicates is the rooting depth possibilities of certain species in their natural habitat, whether that be shallow soils over tuff on mesa tops or deep alluvium soils in canyon bottoms. Certain species discussed in this report such as saltbush (*Atriplex canescens*) and squawberry (*Rhus trilobata*) grow naturally in both types of habitats.

Figures may be useful in making estimates of the range of maximum root lengths (hence, potential depths of root penetration) for a life form on the Pajarito Plateau. Though the data comprising these figures are limited in number, we believe such estimates are more useful than solely extrapolating from published rooting length data that apply to other localities with possibly different growing conditions. Combining site specific field data with data from the literature may be especially useful in predicting the vegetation changes a certain site may experience with climatic change.

For purposes of example, we sometimes refer to commonly known cultivated plants. Only when the plants referred to are native or naturalized in Los Alamos county do we include scientific names. The scientific name follows the common name after its first use in each main section. Thereafter, only the common name is usually mentioned.

Root ecology studies have provided little information regarding those plants which are colonizers or invaders of potential burial sites, or are used in reclaiming sites in the southwestern US (Whicker 1976, Wyatt et al. 1980). Very few root field studies have been conducted since the early, intensive work of Cannon (1911) and Weaver (1926). Only a few of these studies relate to the common southwestern species (Dittmer 1959). The reasons for this paucity of information are evident: root studies are time consuming and labor intensive under field conditions, and, until recently, applications of such studies were directed towards using plants as water-source indicators or towards showing that certain plants are water depletors (phreatophytes).

The present study is an attempt to add to data on the root structure of native species common to the Los Alamos National Laboratory environs, in particular, and to the southwestern US, in general. Many of these species are ones that tend to colonize disturbed areas and to invade uranium mill tailings piles or coal mine spoils; some have been proposed for use in reclamation (Monsen and Christensen 1975); and many of the plants considered here actually grow on low-level waste disposal sites located on Laboratory lands (Tierney and Foxx 1982).

II. SOME BACKGROUND ON ROOT ECOLOGY

A. What is a Root?

Morphologically, anatomically, and physiologically, a plant can be considered as having two life-sustaining systems: an aboveground structure called the *shoot* system; and a belowground structure called the *root* system (Fig. 1). Although distinct, each system depends upon the other for extended survival: roots absorb water and inorganic salts in solution, whereas shoots photosynthesize and transpire. Therefore, the root depends upon the shoot for carbohydrates and growth substances, whereas the shoot depends upon the root for provision of water and minerals (Troughton 1977).

In the simplest definition, a root is that part of the plant that grows downward into the soil, both anchoring the plant and absorbing water and nutrients. However, roots are not always underground structures. The

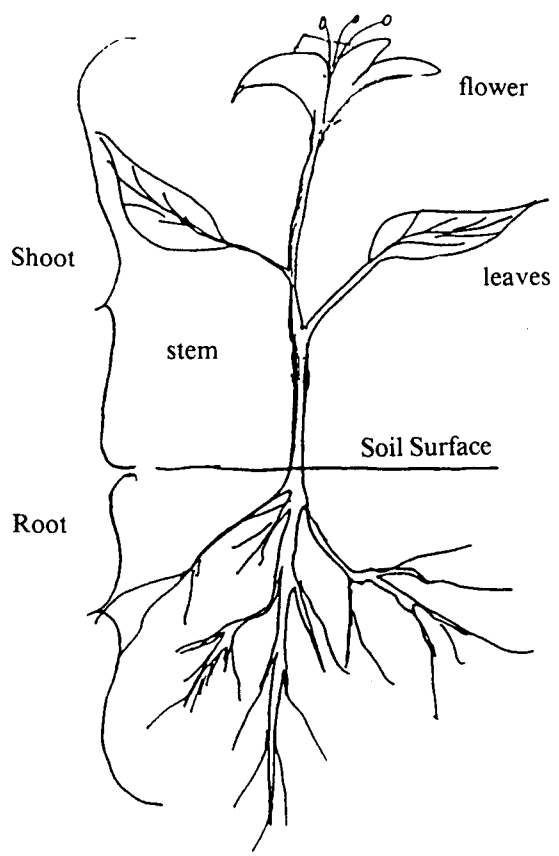

Fig. 1. Plant morphology.

parasitizing roots of the juniper mistletoe (*Phoradendrop juniperum*) are imbedded in the shoot structure of the host plant and the *"prop"* roots of corn (*Zea* spp.) normally remain wholly or partially aboveground. Equally confusing, some underground structures are not roots but shoots. They include *rhizomes, bulbs, corms,* and *tubers* (Fig. 2). From these underground stems roots extend. Roots cannot be distinguished from shoots simply on the basis of position relative to plant and soil. Roots do not ordinarily bear leaves or buds and are not divided into nodes and internodes; but root tissue is capable of developing shoot structures under the right conditions. When the roots of certain plants such as Gambel's oak (*Quercus gambelii*) and the apple tree are exposed at or close to the surface, shoot structures may develop from them.

The main distinction between a root and all other parts of a plant is the presence of a *root cap*, a protective covering over the end of the root (Hill, Popp, and Grove 1967). Main roots or long laterals usually have distinctly pointed root caps, whereas the short absorbing or feeder roots have rounded root caps.

The following outlines the basic differences between roots and stems.

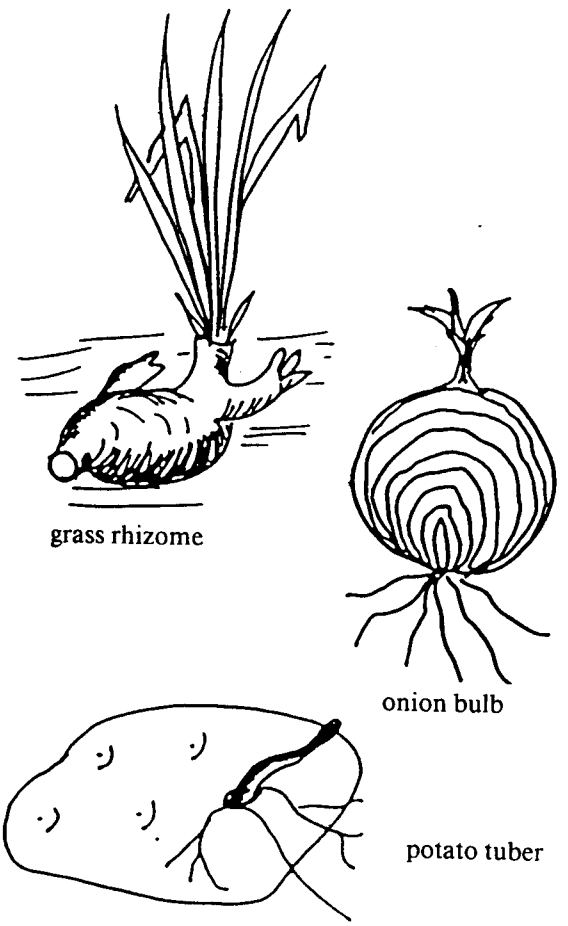

Fig. 2. Underground stems.

Differences Between Roots and Stems

Roots	Stems
1. Roots grow downward into the soil.	1. Stems of most plants grow upward above soil.
2. Roots do not have nodes and internodes.	2. Stems have well marked nodes and internodes.
3. Root branches arise internally from the pericycle tissue.	3. Stems arise externally from buds on the surface of stems.
4. Growing points of roots are covered by rootcaps.	4. Growing points of stems are naked or protected by bud scales.
5. Characteristic appendages of roots are root hairs.	5. Characteristic appendages of stems are leaves and flowers.
6. The primary root originates from the hypocotyl of the embryo.	6. The main stem originates from the epicotyl of the embryo, or in part from the hypocotyl.

B. Classification of Roots

Roots may be classified according to size and development as: *taproots, fibrous* or fleshy roots; as primary, secondary, or lateral roots; and as adventitious roots. The root of a germinating seedling growing downward is the *primary root*, and branches from this primary root are called *secondary* or lateral roots. *Adventitious* roots are those that develop from the nodes of a stem if placed in water, moist earth or sand (Fig. 3). The primary root becomes a *taproot*, largest root of the plant and continues its downward growth, all other roots branching off from it. Dandelion (*Taraxacum* spp.) and salsify (*Tragopopon* spp.) are examples of plants with taproots. If the taproot is further developed as in the cultivated carrots, radishes, and certain wild biennials such as mullein (*Verbascum thapsus*), then it is considered fleshy. Plants such as the annual grasses have no main root, only numerous fine roots because the primary root dies leaving only secondary roots. Root systems of such plants are called *fibrous*.

C. Root Distribution and Development

Individual roots may in certain circumstances extend deep into the soil, but most tree- and shrub-root systems are usually concentrated in the upper 1 m of soil (Weaver and Kramer 1935), whereas the absorbing roots of forbs and grasses are usually concentrated in the upper 20 to 30 cm of soil. Cultivation and deep watering may alter the growth of roots and stimulate the development of deep-root systems. On the other hand, fertilization tends to increase root development in the uppermost soil horizons (Hermann in Marshall 1977).

Root distribution may also vary in time. Numerous studies (for example, Preston 1942) have shown that constant change is the rule in root systems of trees. Except for taproots and large lateral roots that usually persist, substantial portions of the root system die back periodically and allow new systems to develop. Studies of variation and flexibility in root systems (for example, Weaver 1919, Pulling 1918) indicate a considerable variation among species in this regard. Some species remain constant and others exhibit plasticity in development of root structures. In particular, the flexibility in soil penetration appears to be an important factor in determining the natural geographic distribution of a particular species. Other edaphic factors may determine root penetration and absorption: soil pH, soil type (Holch 1931), groundwater level (Nedrow 1937), and the presence of hardpan. An understanding of these factors as well as knowledge of the rooting habit of the species is, therefore, necessary to estimate the depth and extent of root penetration.

A related question is the ratio of belowground biomass (root biomass) to aboveground biomass (the mass of the plant developed as shoots, stems, leaves,

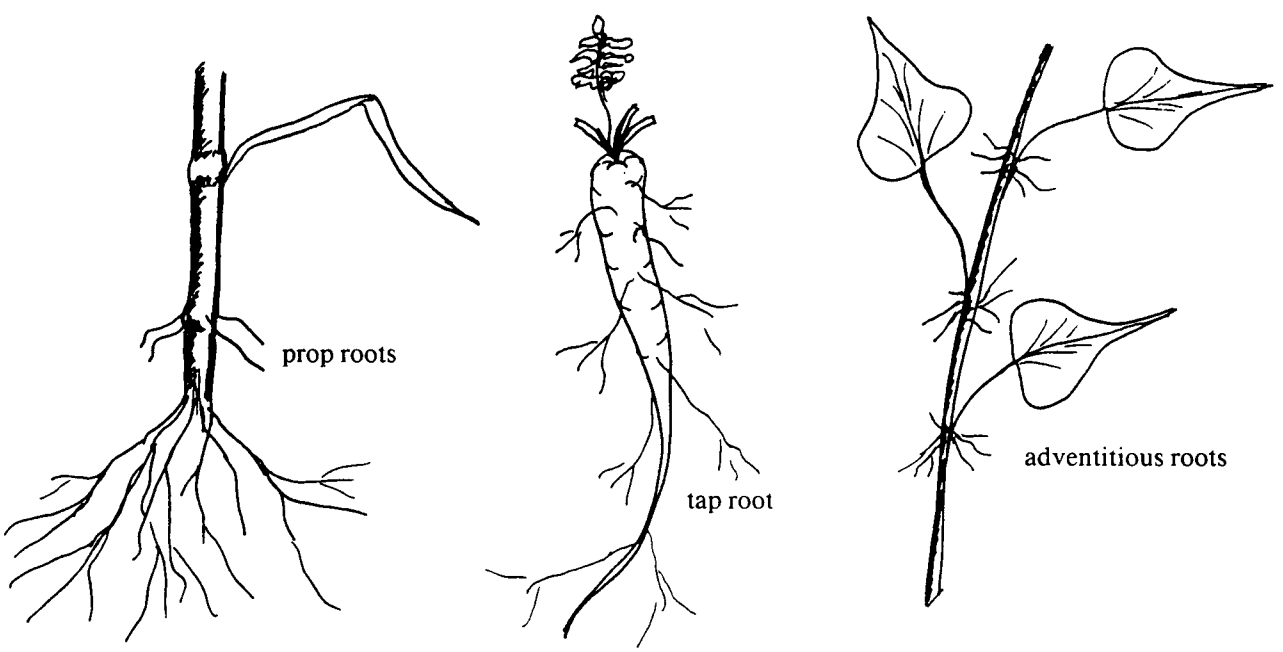

Fig. 3. Types of roots.

etc.). Are there any regularities to this ratio, and if so, what ecological and edaphic factors correlate with those regularities? Caldwell and Fernandez (1975) studied a cool desert shrub community in northern Utah and found that 90% of the biomass is belowground (a root-to-shoot ratio of 9 to 1); whereas Reichle and his colleagues (1973) obtained a root-to-shoot ratio of about 1 to 10 for the mesic hardwood-forest ecosystem at Oak Ridge National Laboratory. Warm desert communities appear to have a root-to-shoot ratio less than unity (Barbour 1973), though data from the USSR desert and steppe areas indicate ratios nearer those found for cool desert shrub communities of northern Utah. Given this level of disparity in the empirical data, the ecological factors determining root-to-shoot ratios are apparently still poorly understood.

Although no measurements of biomass ratio were made during the field work connected with the present report, the author's superficial and visual impression is that the root-to-shoot ratio for the semiarid, juniper-piñon woodlands of northern New Mexico is nearly unity. As a substitute for root-to-shoot measurements, Foxx et al. (1984a) used a computerized data base of 409 trees to examine the ratio of rooting depth to plant height. The d/h ratio for 392 deciduous trees was 0.42, and the d/h ratio for 17 evergreen trees was found to be 0.57. Information was found on the d/h ratio for 15 shrubs, 10 grass specimens, and 34 forb specimens. The d/h ratios were 1.2, 2.0, and 1.7, respectively.

III. STUDY AREAS AND METHODS

The field work for this study was conducted in the summer of 1981 on Los Alamos National Laboratory land on the Pajarito Plateau. The plateau is a mesa and table land on the eastern flank of the Jemez range in Los Alamos, Sandoval, and Rio Arriba Counties, New Mexico.

The Pajarito Plateau is composed mostly of volcanic tuff and basalt that overlies older sedimentary materials. Canyons have been cut through the tuff and sediment to form a series of interlacing valleys, buttes, and mesas, all roughly oriented in a west-to-east direction. Elevation of the parts of the plateau relevant to this study range from 1981 to 2134 m. The climate is semiarid; total precipitation averages 45 cm per year at the upper edge of the plateau and about 34 cm per year at the lower reaches. In 1981 the total precipitation was 45 cm in the upper portion, arriving mostly in July and August. The record for the lower plateau is incomplete for this year. Maximum and minimum temperatures recorded in 1981 were 35° and −16°C, respectively (Environmental Surveillance Group, HSE-8, 1982). The natural plant communities on the parts of the plateau relevant to this study are piñon-juniper woodland interspersed with grasslands at the lowest elevations and ponderosa pine forests at the higher elevations.

A. Descriptions of Study Areas

Field work for the root-depth studies to be described was concentrated in four areas within Los Alamos National Laboratory land: Pajarito Canyon, Potrillo Canyon, Mesita del Buey, and Mortandad Canyon. The locations of these areas and the root excavation sites are shown in Fig. 4.

- **Pajarito Canyon** extends from the Jemez Mountains on the west at an elevation of about 2743 m to the Rio Grande on the east at 1829 m. Soil in this canyon near the excavation site appeared to be a sandy loam interspersed with gravel beds and river cobbles. The sandy loam generally occurred to depths of 60 cm, whereas below the sand layer, large river cobbles were predominant to at least 160 cm. The bottom of the canyon is occupied by an intermittent stream, and at least seven intermittent springs (seeps) are known to surface along the canyon's course. Prehistoric ruins frequently are found on the northern wall of the canyon; some prehistoric garden plots outlined in rock were noted about 3 miles south of the excavation site. Historically, the canyon contained a ranch with pastures and gardens.

  The natural plant community near the excavation site is predominantly a piñon-juniper woodland (*Pinus edulis—Juniperus monosperma*), with some old ponderosa pine (*Pinus ponderosa*) interspersed on the north-facing canyon slopes. Other species in the immediate vicinity of the excavation were big sagebrush (*Artemisia tridentata*), Apache plume (*Fallugia paradoxa*), Rocky Mountain juniper (*Juniperus scopulorum*), New Mexico olive (*Forestiera neomexicana*), and cheat grass (*Bromus tectorum*). Across the road from the excavation site there was a small community of narrowleaf cottonwood (*Populus angustifolia*), willow (*Salix* spp.) and cattail (*Typhus latifolia*).

- **Potrillo Canyon** (Fig. 5) is a shallow, wide canyon lying south of Pajarito Canyon. The excavation site was in the opening of Potrillo Canyon just east of State Road 4. The elevation of the excavation was about 1920 m. Surrounding the excavation site there appeared to be prehistoric fields. A modern borrow pit for topsoil was located nearby.

  Soil at the excavation site was a sandy loam, about 1.5 m deep, underlain by coarse sand and pumice. The vegetation was dominated by piñon pine (*Pinus edulis*) and one-seed juniper (*Juniperus monosperma*)

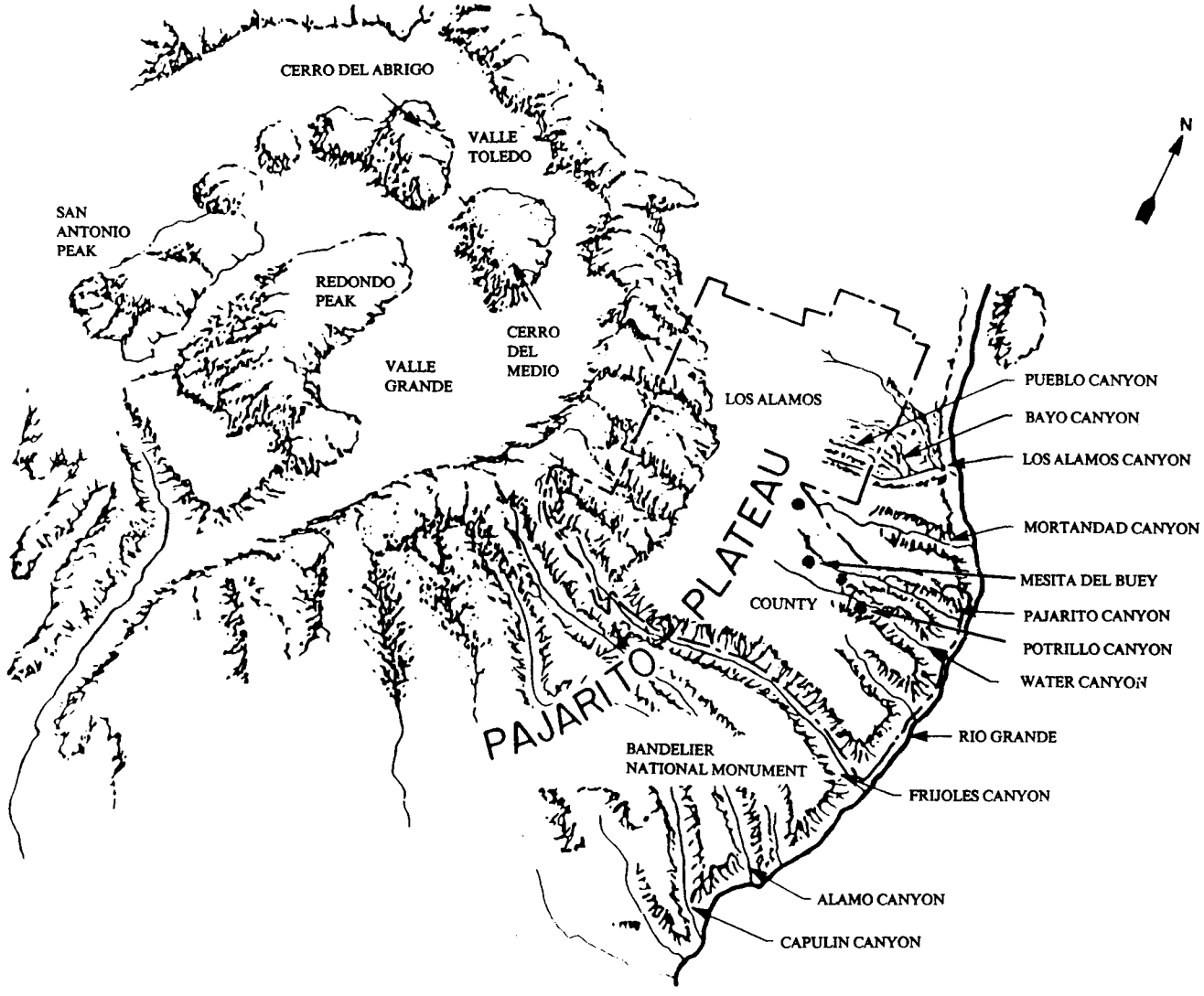

Fig. 4. Physiographic setting of root excavation sites.

Fig. 5. Potrillo Canyon.

but Rocky Mountain juniper (*Juniperus scopulorum*) and ponderosa pine (*Pinus ponderosa*) were also present. Other plants seen near the excavation site were big sagebrush (*Artemisia tridentata*), pinque (*Hymenoxys richardsonii*), false tarragon (*Artemisia dracunculus*), snakeweed (*Gutierrezia sarothrae*), blue gilia (*Ipomopsis longiflora*), and James buckwheat (*Eriogonum jamesii*).

- **Mesita del Buey** (Fig. 6) forms the northern rim of Pajarito Canyon and the southern rim of Mortandad Canyon. Soils on this tuff-capped mesa are generally shallow and rocky except in isolated pockets and basins. The western part of the mesa near the excavation site had been considerably disturbed by construction of experimental waste disposal sites. However, the waste disposal sites were placed among stands of piñon and juniper that were by-and-large undisturbed. Elevation of the excavation site was about 2134 m.

Common native plants seen at the excavation site were prickly pear (*Opuntia polyacantha*), currant (*Ribes cereum*), pinque (*Hymenoxys richardsonii*), wild chrysanthemum (*Bahia dissecta*), mountain mahogany (*Cercocarpus montanus*), little bluestem (*Andropogon scoparius*), snakeweed (*Gutierrezia sarothrae*), estafiata (*Artemisia frigida*), blue grama (*Bouteloua gracilis*), and deervetch (*Lotus wrightii*). Some obvious disturbed area species occupied piles of excavated earth near the site. These were Fremont's goosefoot (*Chenopodium fremontii*), tumbleweed (*Salsola kali*), cutleaf evening-primrose (*Oenothera coronopifolia*), and the common sunflower (*Helianthus petiolaris*).

- **Mortandad Canyon** (Fig. 7) is the broad canyon north of Mesita del Buey. Notable features of the canyon are the prehistoric cliff dwellings on the southern canyon face and indications of flood-water farming (both prehistoric and historic) on the canyon's bottom lands. Two excavation sites were located in this canyon. The soils of the site in the upper canyon were deep loamy sand; the soils at the second site, one-fourth mile to the east of the first group of trenches, were loamy sand to a depth of 30 cm, followed by dense clay, hardpan, and finally a coarse sand to indefinite depths. The elevations of the first and second excavation sites in Mortandad Canyon are 2194 and 2164 m, respectively.

Vegetation on the north-facing slope of the canyon was dominated by ponderosa pine (*Pinus ponderosa*) and Gambel's oak (*Quercus gambelii*); on the south-facing sides and mesa tops the vegetation is mostly

Fig. 6. Mesita del Buey.

Fig. 7. Mortandad Canyon.

Fig. 5. Potrillo Canyon.

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Fig. 6. Mesita del Buey.

Fig. 7. Mortandad Canyon.

piñon pine and one-seed juniper. The canyon bottom supports populations of chamisa (*Chrysothamnus nauseosus*), some big sagebrush, but mostly the lower growing wormwood (*Artemisia ludoviciana*), false tarragon, squawberry (*Rhus trilobata*), blue grama grass (*Bouteloua gracilis*), and some scattered stands of large ponderosa pine.

B. Field Methods

Our initial choice of species for study was based on our experience in the vegetation mapping of five low-level waste burial sites at Los Alamos (Tierney and Foxx 1982), and two useful sources in the literature: a study by Dreesen and Marple (1980) of ^{226}Ra in vegetation colonizing uranium mill tailings, and a report by Wagner et al. (1978) on natural succession on strip-mined land. These sources discuss plants that grow in the proposed study area on Los Alamos National Laboratory lands. The major constraint was locating areas where selected species grew that would be accessible to a backhoe and were hidden from public roads so that excavations would not be visible. Furthermore, the density of prehistoric sites on Laboratory lands is so great that each of our excavation sites had first to be examined and then cleared by the Laboratory archeologist before digging could begin. The seven sites located in the four study areas discussed in Section III.A were finally chosen because they met the major constraints.

Plant species were identified at the excavations sites. Excavations were planned so that one trench would uncover the root systems of as many specimens as possible. The width and height of each specimen was recorded before excavations began. The entire plant was then photographed in place after the backhoe had dug a trench to within 30 cm of the plant base. The backhoe was used to dig a trench about 1.5 m wide and 3 m long (Fig. 8). Excavations were seldom more than 3 m deep because of the possibility of cave-ins in the alluvial soils (Fig. 9). The remainder of the excavation of plant roots was done with hand tools. Care was taken to excavate the stoutest (top or primary) roots to the longest extent as was possible. Sometimes the entire length of the root was excavated intact but more often the root was broken at the bottom of the trench. In most of the trenches, constant sloughing in of the walls precluded finding and excavating the roots further. Lateral roots were only followed to the horizontal ends of the trenches (3 - 4.5 m) to determine if they turned downward or had secondary roots turning downward to become substantial vertical roots. Oaks and ponderosa pine both displayed

Fig. 8. Backhoe digging trench.

Fig. 9. Excavating roots in trench.

the phenomena of horizontal roots either turning downward or substantial secondary roots descending from horizontal roots.

After the largest roots had been uncovered or delineated, the entire plant was raised as far as possible, photographed, and the rough dimensions of its root system were measured. Root lengths were usually measured to the nearest 5 cm; root diameters were measured to the nearest millimeter. All major roots were then clipped off in 10-cm lengths and packaged for later study. The caudex also was saved for possible dating of the specimen.

IV. ESTIMATION OF ROOT LENGTHS OF BROKEN ROOT SPECIMENS

In conjunction with this field study, an annotated bibliography of root depth and root ecology was prepared (Foxx et al. 1984a, Foxx et al. 1984b). The following attempt at estimating rooting depth from broken specimens was made so that this work and the bibliographic data could be compared.

Almost all of the largest roots retrieved in the field broke at some point along their length before we were able to dig to their termination point (the growing tip or root cap). In all cases, extensions of the largest, sturdiest roots near the caudex of the plant were the roots that were to be found at the lower part of the excavation. No smaller, fragile roots from the caudex continued very deeply. The difficulty of breakage is illustrated in the root-profile plots in the next section. To estimate the true length of these broken roots, several formulae were evaluated for predicting the length of the root, based on measurements of mean root diameters at points "upstream" from the break point; all of these formulae are variations of the simple conical formula that approximates the shape of a root by a truncated cone, as shown below in profile through the axis of symmetry (Figure 10).

The variable r_1 is the average root radius (1/2 average root diameter) at some point a distance l_1 below the caudex; r_2 is the average root radius at the break point that lies a distance $l_1 + l_2$ below the caudex; r_c is some cut-off radius chosen to take into account the fact that the larger roots are seldom conical in shape near the root cap (see discussion of root shape below). With these definitions, the simple conical formula gives L, the estimated length of the entire root, as

$$L = l_1 + l_2 \frac{(r_1 - r_c)}{(r_1 - r_2)} .$$

the formula that we used to estimate the entire root length from samples of broken roots.

The simple conical formula seems to work best with the kinds of roots that we studied in spite of its oversimplification of root geometry and the use of only two diameters from the set of measurements available from the root-profile plots. Tests of this formula were made using two entire roots for which hypothetical "break" points were postulated and the estimated root lengths were calculated and compared with the measured root lengths. The estimates were found consistently to be within 10% of the measured lengths. However, some subjective judgment is necessary in using the simple conical formula: one must choose the distance, l_1, below the caudex and the cut-off radius, r_c, according to the particular sample and species. In practice, the choice of r_c (about 0.5 mm) turns out not to be critical because it is much smaller than r_1.

Even idealized root profiles, in which knots and kinks are automatically eliminated by averaging, do not show

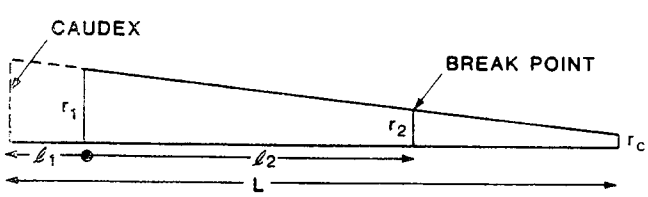


Fig. 10. Schematic profile of root through the axis of symmetry.

a conical shape. The idealized profile is more like an awl or railroad spike if the caudex and root cap are included. The average diameter decreases rapidly in the first 10 to 20 cm of length below the caudex; there is then an almost-constant-slope segment, followed by an almost-parabolic root cap. The almost-constant-slope segment is usually the longest part and is best fit by the shape of a truncated cone. Thus, formulae that include measurements of the caudex and the concave region just below it are likely to give underestimates of the entire root length. An example of such a formula is

$$L = \frac{r_1 - r_c}{s} ,$$

where r_1 is the caudex mean radius, r_c is the cut-off radius mentioned above, and s is the sample mean of the slopes of the root profile taken along equal segments of root length, as

$$s = \frac{1}{n} \sum_{i=1}^{n} \frac{\Delta r_i}{\Delta l} ,$$

where n is the sample size and the Δr_i are the differences in root mean radius over equal-length segments Δl. This formula was applied to the two entire "test" roots mentioned above; it was found that the root lengths were underestimated by 50 to 60%.

We further note that the simple conical formula may not always be applicable because of individual variation in samples and the points where the samples are broken.

V. DATA ON ROOT LENGTHS AND MORPHOLOGY

Data on root lengths and root morphology of 22 plant species commonly found on Laboratory lands were obtained. Table I lists the species for which root samples were obtained and the excavation sites where the samples were gathered. Those designated with an asterisk (*) have been recorded as being present on restabilized low-level waste sites (Tierney and Foxx 1982); or are known to colonize uranium mill tailing piles in the southwest; or are potential colonizers of disturbed areas of the Pajarito Plateau. The remaining species, included because they were in the path of the backhoe, are species common to this area.

The following section represents data collected for each species (Table I). The information includes descriptions of rooting habits (Appendix A) and gross morphology (Appendix B) as observed during and after excavation of the plants, root measurements as taken, and root profiles as determined by measurements every 10 cm along the excavated root length. Estimated root lengths were determined by the formula discussed in Section IV. Drawings of root habit were made by projecting photographic slides of the plants (obtained in situ or after excavation) on paper and tracing the rooting patterns. This was done because the photographs themselves did not show enough contrast between the root and soil. The scale in each picture represents 10 cm increments. Close-up photographs for gross root morphology were taken with a 50-mm macro lens after the roots had dried. This allowed for easier removal of adhering soil.

The following information on each plant is included in the descriptions:

Location: Area or areas from which specimens were collected.

Soils: General observations on the nature of the soil at the excavation site.

Habit: General growth form of the plant.

Plant Description: A nontechnical description of the species based on the external form. Descriptions and accompanying drawings are modified from Foxx and Hoard (1984).

Range: General location (elevation and habitat); where the plant is found in the ecosystem.

Rooting Habit: Represents the type of root, tap or fibrous, and the observed rooting patterns of the plant at the excavation site.

Gross Root Morphology: General description of observed external and internal root anatomy. Much of the root descriptive terminology adapted from Gilbertson (1961).

Specimen Age: Specimen age was determined from growth rings when possible.

Literature: Literature values (as found by Foxx et al. 1984a, 1984b) for rooting depths are included here for comparison with rooting depths found in our excavations.

Root and Crown Measurements: Here, shown in tabular form, are the actual measurements of the specimens excavated.

Estimated Root Lengths: Discussion of an approach to estimating root length is in Section IV.

TABLE I

SPECIES FOR WHICH ROOT SPECIMENS WERE OBTAINED AND LOCATIONS AT WHICH SPECIMENS WERE GATHERED

Common Name and Scientific Name	Number of Specimens Obtained				
	Pajarito Canyon	Potrillo Canyon	Mesita del Buey	Mortandad Canyon No. 1	Mortandad Canyon No. 2
Trees					
*piñon, *Pinus edulis*	---	1	1	---	---
*ponderosa pine, *Pinus ponderosa*	---	---	---	---	2
*one-seed juniper, *Juniperus monosperma*	---	---	1	---	---
Shrubs					
*chamisa, *Chrysothamnus nauseosus*	---	---	---	3	---
*squawberry, *Rhus trilobata*	---	---	---	---	2
*Apache plume, *Fallugia paradoxa*	3	---	---	---	---
*mountain mahogany, *Cercocarpus montanus*	---	---	1	---	---
*Gambel's oak, *Quercus gambelii*	---	---	3	---	1
big sagebrush, *Artemisia tridentata*	2	2	---	---	---
wax currant, *Ribes cereum*	---	---	1	2	---
*New Mexico locust, *Robinia neomexicana*	---	---	---	---	2
fourwing saltbush, *Atriplex canescens*	---	---	2	---	---
Subshrubs					
*snakeweed, *Gutierrezia sarothrae*	---	---	2	---	---
*estafiata *Artemisia frigida*	---	1	---	1	---
*narrow leaf yucca, *Yucca angustissima*	---	---	1	1	---
Forbs					
*prickly pear, *Opuntia polyacantha*	---	--	---	3	---
*pinque, *Hymenoxys richardsonii*	---	---	1	1	---
*mullein, *Verbascum thapsus*	---	---	---	---	2
*sunflower, *Helianthus petiolaris*	---	---	1	---	---
*Fremont's goosefoot, *Chenopodium fremontii*	---	---	1	---	---
*lupine, *Lupinus caudatus*	---	---	---	1	---
Grass					
*blue grama, *Bouteloua gracilis*	---	---	---	2	---

*Found on low-level waste sites (Tierney and Foxx 1982).

Root Profile: Graphs are created from data collected by measuring the root diameter every 10 cm along the total length and estimating the total length by formula described in Section IV.

Plants are arranged as to growth form: trees, shrubs, subshrubs, forbs, and grasses. Specimens of three different species of trees were excavated. All species representing the dominant overstory are also found on older, more stabilized waste sites (Tierney and Foxx 1982). Because of size (many reach 15 m or more) all excavated specimens were immature (121 to 183 cm).

Specimens of nine different species of shrubs were excavated in the four different locations. Most of the shrubs are represented in later stages of invasion onto stabilized low-level waste sites at Los Alamos.

Subshrubs or undershrubs are usually less than 45 cm tall. They are often shrublike perennials that have woody bases. Specimens of three different subshrubs were collected.

Perennials have a life cycle that extends over more than one growing season. Biennials complete the life cycle within two growing seasons. One perennial grass, one biennial grass, and two perennial forbs were collected: rooting depths of other perennials along the trench were noted. Annuals have a life cycle completed in one growing season. Rooting depths of two annual forbs were noted.

VI. GENERAL OBSERVATIONS AND DATA ANALYSIS

A. General Observations

1. Roots and Gopher Holes. On several occasions gopher holes were found in the walls of the pits. Gopher holes were encountered at 95-110 cm. Roots of ponderosa pine were observed extending into a gopher hole. Roots were spiral in shape and followed the curvature of the wall of the hole (Fig. 11).

2. Roots and Cracks in the Tuff. Soils on the mesa tops are shallow and underlain by tuff. Roots of various species were observed to penetrate through the soil to the soil-tuff boundary. They then followed along soil-tuff boundary until a crack or fracture in the tuff was encountered. The roots descended abruptly into the crack (Fig. 12). At a pit being prepared for waste burial, we observed roots of piñon, juniper, and oak following such fracture lines in the tuff. Piñon and juniper roots were traced to depths greater than 6 m. At those depths the roots were 1 to 3 mm in diameter.

Lateral deflection of roots by a clay layer were also observed in an arroyo in Sandia Canyon (Fig. 13). Foxx et al. (1984a) found the shallowest rooting specimens in clay soils. An occasional deep rooting specimen occurred only when the impervious layers cracked and the roots could follow water pathways through the cracks.

3. Observations of Roots in Road Cuts or Arroyos. Rooting depths of trees, shrubs, forbs, and grasses were observed in road cuts and along arroyos. The undercutting of an arroyo in Sandia Canyon provided the best observations. Roots of wax currant (*Ribes cereum*) were seen to descend to 3 m along the arroyo and those of New Mexico Locust (*Robinia neomexicana*) extended to a depth of 4 m. Most of the roots of a ponderosa pine [63 cm at breast height (DBH)] were observed to be within the first 2 m of soil, but at 2 m the large roots extended laterally. This rooting behavior was repeatedly observed in excavation pits and road cuts. In Sandia Canyon a piñon pine, 1.5 m tall, had roots down 3 m; at 3 m the roots were only 1 cm in diameter. In the same area, roots of Gambel's oak extended 2 m (Fig. 14).

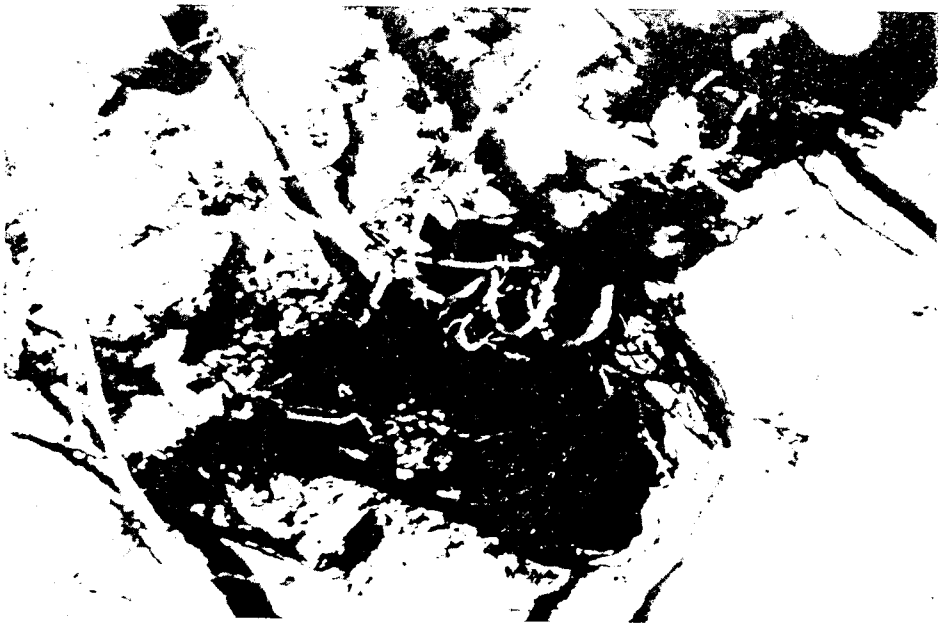


Fig. 11. Ponderosa pine roots in gopher hole.

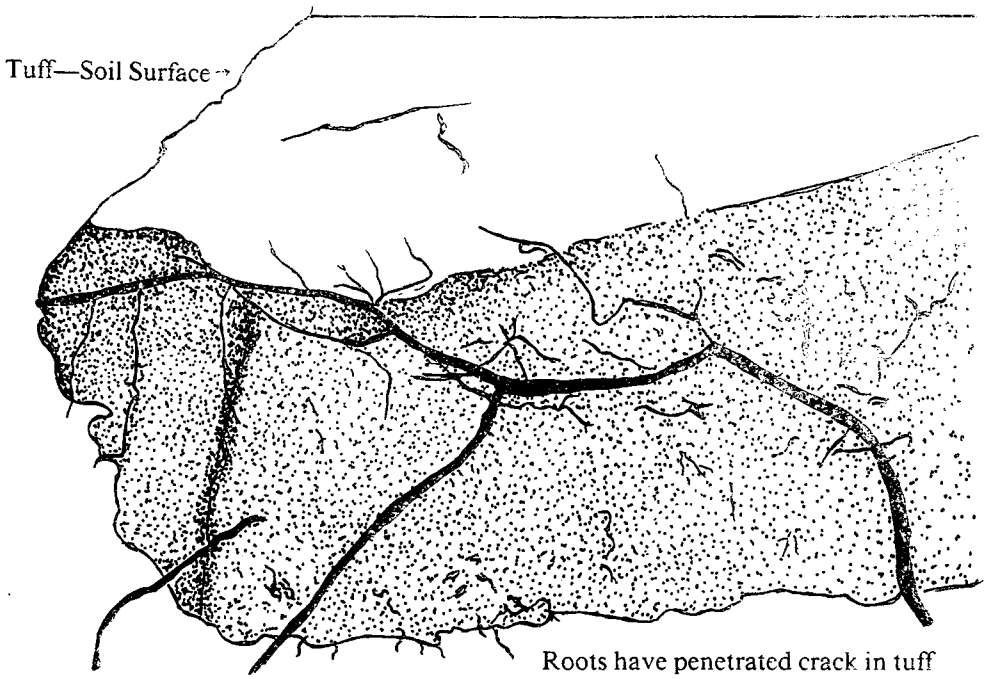


Fig. 12. Tuff block with roots in cracks.

Fig. 13. Lateral deflection of roots by clay layer.

Fig. 14. Roots exposed by arroyo cutting.

4. Rooting Depth of Large Ponderosa Pine. General observations concerning rooting patterns of mature ponderosa pine indicate that the mass of roots are within the first 3 m of soil. Berndt and Gibbons (1958) reported a tree 8 m tall as having a rooting depth of 1.7 m. Lateral root growth is much more extensive; usually extending approximately the distance of the height of the tree. Numerous observations of roadcuts and upturned trees indicate a shallow rooting habit.

B. Comparison of Rooting Depths

The rooting depths of species on Laboratory lands, for the most part, could not be followed to their limit because of safety considerations and/or soil profiles. Table II compares the values found in this study and the literature values summarized by Foxx et al. (1984b).

In general, the greatest observed biomass of the roots of all trees, shrubs, and forbs were located in the upper 2 m of soil and annual and perennial in the upper 1 m. Rooting habit studies for most species showed one or two roots penetrated deeply, these were usually 1 to 3 mm in diameter at their greatest length.

C. Root Depth to Shoot Height

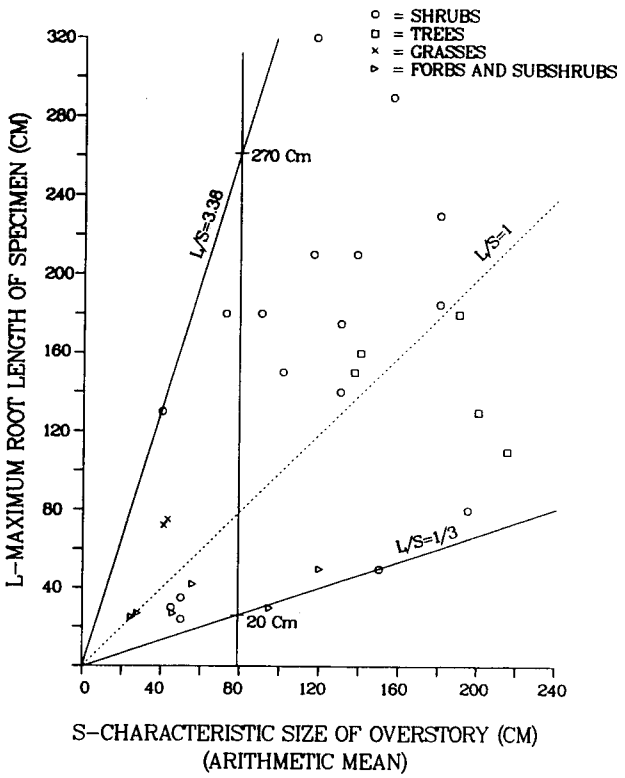
The sample sizes for roots of the individual species were too small to afford statistically significant estimates of root lengths. For this reason, we have pooled our measurements of root lengths according to the four life forms exhibited by 22 species: shrubs, trees, grasses, and a single life form that includes subshrubs and forbs (perennial, biennial, and annual varieties). Furthermore, to account for the possibility that our root specimens were taken from immature individuals, we were compelled to compare the root lengths of specimens with some other dimension of the specimen that is likely to be correlated with state of growth and the common ecological variables such as exposure and soil depth. The dimension with which we compare root length is here taken as the *characteristic overstory size*, defined as either the arithmetic or geometric average of overstory (or shoot) height of specimen and overstory (or shoot) diameter of specimen.

A scatter plot of L, the actual or inferred maximum root length, versus S, the characteristic overstory size, is shown in Fig. 15. The identity of the sample species is

TABLE II

COMPARISON OF ROOTING DEPTHS OF SPECIES WITH LITERATURE VALUES

	Los Alamos Values		Literature Values	
Common Name and Scientific Name	Measured (cm)	Estimated (cm)	Average (cm)	Range (cm)
one-seed juniper, *Pinus edulis*	50,60,50,30	110,130	---	---
ponderosa pine, *Pinus ponderosa*	150,130	160,150	447	10-2438
one-seed juniper, *Juniperus monosperma*	150	170	2438	579-6096
chamisa, *Chysothamnus nauseosus*	100,200,180	140,180,210	293	100-457
squawberry, *Rhus trilobata*	150,170	210,230	---	---
Apache plume, *Fallugia paradoxa*	90,130,60	170,290,260	---	---
mountain mahogany, *Cercocarpus montanus*	40	50	113	40-152
wax currant, *Ribes cereum*	150,100,70	290,80	---	---
New Mexico locust, *Robinia neomexicana*	140,100	---	---	
oak, *Quercus spp.*	100,80,50,45	320,150,175	238	80-396
fourwing saltbush, *Atriplex canescens*	70,110,60	185,220	392	80-762
big sagebrush, *Artemisia tridentata*	10,40,110,150	130,180	248	110-914
snakeweed, *Gutierrezia sarothrae*	90,130,60	170,290,260	122	51-244
narrowleaf yucca, *Yucca angustissima*	10,10	---	112	40-152
prickly pear, *Opuntia polyacantha*	28,10,8	---	77	2-366
mullein, *Verbascum thapsus*	28,42	---	---	---
sunflower, *Helianthus petiolaris*	40,45	---	69	---
Blue grama, *Bouteloua gracilis*	53,58	---	119	38-396



Example: Measured characteristic overstory size of given life form is 80 cm; we might then infer that the range of maximum root lengths is 20 cm to 270 cm for that life form on the Pajarito Plateau.

Fig. 15. Root depth to shoot height.

not shown; rather, each sample is plotted according to whether it is a shrub, tree, grass, and a forb or subshrub. Except for the two grass samples, characteristic overstory size was computed from the arithmetic mean of height and diameter. The overstory geometry of the plants measured were sufficiently near to spherical that use of the geometric mean in place of the arithmetic mean made little difference in the construction of Fig. 15.

The three radiating lines on Fig. 15 delineate regions where L/S assumes values less than, equal to, or greater than 1. Above the central line, L/S = 1, root lengths are larger than characteristic overstory size; the maximum value of L/S among our samples is 3.38. Below the central line, L/S = 1, root lengths are smaller than characteristic overstory size; the minimum value of L/S among our samples is about one-third.

Figure 15 shows that shrubs on the sites we surveyed tend to have the longest roots relative to their overstory dimensions. In our samples, maximum L/S was measured for big sagebrush (*Artemisia tridentata*), Specimen No. 3, from Pajarito Canyon. The second largest value for L/S (2.74) came from a sample of Gambel's oak (*Quercus gambelii*) found on Mesita del Buey. Most of the shrub samples were mature individuals. The shrub samples are representative of the local plant community under similar edaphic conditions favoring the presence of older plants. These shrub populations are at least 20 years old. Because mature individuals of the shrub-like species can attain characteristic overstory sizes as large as 3 m on the Pajarito Plateau, our data suggest that larger roots of shrubs could penetrate at least 6 m of soil under favorable conditions. Such penetration depths are consistent with the values from the literature.

The trees represented in our samples tend to have L/S values near or less than one. Generalizations on the basis of the five roots measured combined with observations of piñon and ponderosa roots in deep road cuts tend to reinforce the impression that L/S is nearly unity for typical trees of the Pajarito Plateau. The individuals we were able to measure were undoubtedly immature, because individuals in mature stands of juniper, piñon, and ponderosa typically have overstory sizes of the order of 3 to 30 m. For the record, the tree species showing the largest L/S value (1.11 to 1.14) was the ponderosa pine, while the species showing the least L/S values (0.54 to 0.65) was the piñon pine.

The data for grasses, forbs, and subshrubs shown in Fig. 15 are consistent with what is already known about the root depths of these life forms. The root zones of annuals and small perennial plants in the forest understory seldom exceed 1 m in depth. Our limited data further show that L/S values for forbs and semishrubs, at least in our area, are probably less than or equal to 1.

VII. SUMMARY

The root lengths, rooting habit, and gross root morphology were examined for 21 species of plants common to the Los Alamos National Laboratory lands. Many of these species are late successional invaders onto stabilized low-level waste sites. Because of penetration, rooting patterns are important to long-term stabilization of the trench cap and to the water balance within the trench.

The rooting patterns of three tree species were examined. Roots of both piñon pine and one-seed juniper were found to extend to depths greater than 6 m in fractures in the tuff. Roots of immature specimens were found within 2 m of the soils surface.

Large roots of ponderosa pine were nearly always found within the first 2 m of the soil surface. Observations in arroyos and road cuts indicated that there was extensive lateral growth of the roots of this tree species. Immature specimens were found to root to less than 2 m.

The deepest rooting shrubs were those that had very little lateral root formation: chamisa, Apache plume, and oak. These species usually had one large elongated taproot rooted to depths greater than 2 m. New Mexico locust appeared to have the shallowest roots because of considerable lateral root development. In this species, lateral roots often produced sprouts for new shoot growth. Similar characteristics were found occasionally in Gambel's oak and Apache plume.

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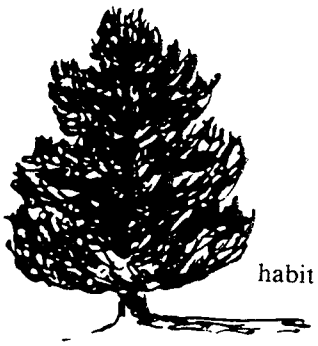
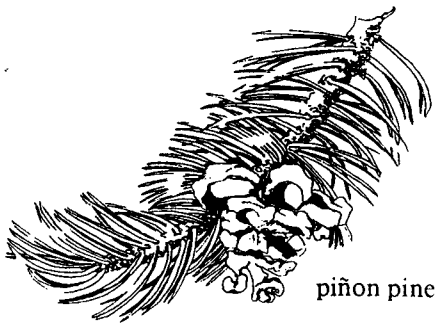
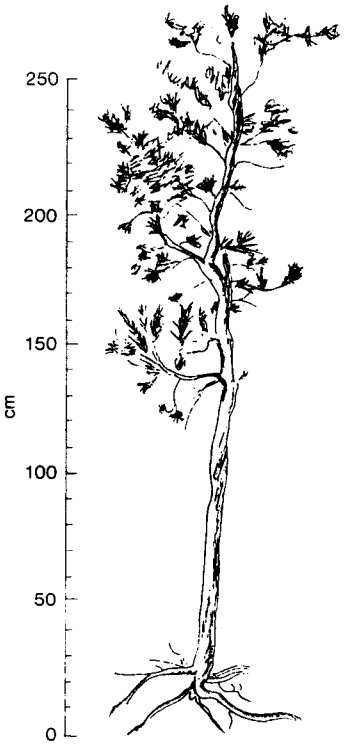
Appendix A. Plant Description, Root Morphology, and Measurements







Piñon pine (*Pinus edulis*)

Location: Two specimens of piñon excavated at Mesita del Buey (Specimen No. 1) and Potrillo Canyon (Specimen No. 2).

Soils: Soils on Mesita del Buey were 30 cm deep, mainly clay loam underlain by tuff.

Habit: A tree with full branching all along trunk. When not crowded or damaged, broadly pyramidal when young, globose with age.

Plant Description: Bushy, evergreen tree, to 10 m tall. Needle-like leaves usually two to a bundle. The top-shaped cones open in September, releasing nutlike edible seeds.

Range: Dominant tree of the piñon-juniper woodland. Generally found at altitudes of 1981 to 2086 m.

Rooting Habit: Most roots were laterals. The taproot bifurcated within a few cm of the surface, becoming several roots growing downwards, then turning laterally at 40-cm depths. Laterals emerge directly from caudex.

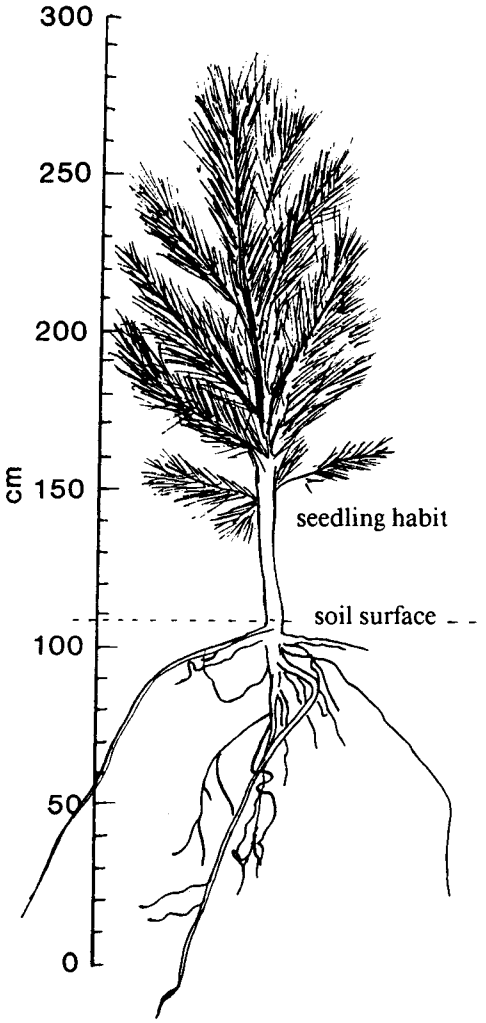
Gross Root Morphology: Bark loosely adhering, in 2 to 3 layers; bark breaking and spalling into irregular platelets, yellow-orange and tending to curl up at edges.

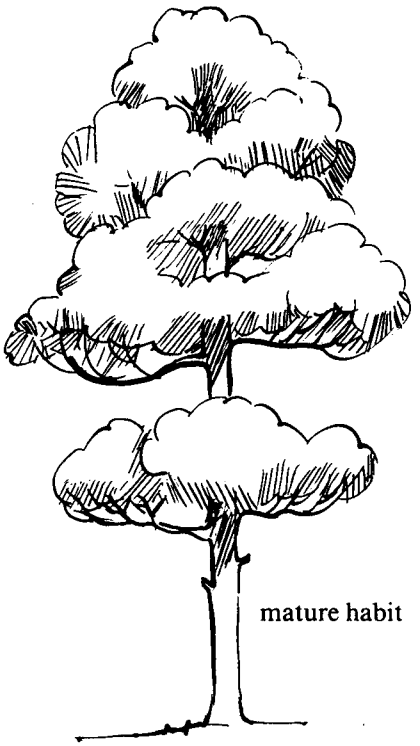
Specimen Age: 50-60 years.

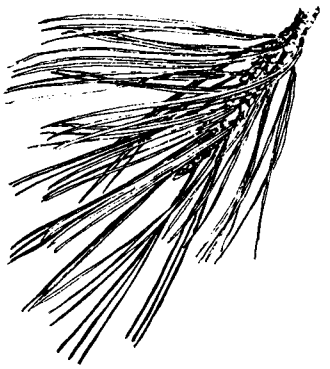
Literature: No values found.

ROOT MEASUREMENTS OF PINON PINE

Specimen No.	Shoot Height (cm)	Crown Diameter (cm)	DBH (cm)	Caudex Diameter (cm)	Measured Root Length (cm)	Estimated Maximum Root Length (cm)
1	319	90	6.5	10	50 (broken)	110
2	300	100	7.0	13	60, 50 ,30 (laterals broken)	130 for 60 cm measured root







ponderosa pine branchlet

Ponderosa pine (*Pinus ponderosa*)

Location: Two immature specimens of ponderosa pine excavated at Mortandad Canyon.

Soils: Alluvial, sandy loam.

Habit: An erect, single trunk tree branching irregularly, mostly from the upper half.

Plant Description: Tall tree up to 70 m; 152 to 244 cm in diameter. Branches stout, thick and somewhat drooping. Older bark yellow-brown with a vanilla odor. Cones 7 to 13 cm long, red-brown with prickly scales; seeds winged.

Range: Occurs in nearly pure stands at altitudes of 2134 to 2438 m; along streams at lower elevations. Scattered throughout the mixed conifer forest at higher elevations.

Rooting Habit: The taproot appears to descend to less than 2 m, then branch into numerous laterals; laterals also extend from caudex. In larger trees (as observed on road cuts and steep canyon ridges) there is no taproot, only a concave-bottom caudex from which roots extend mostly laterally.

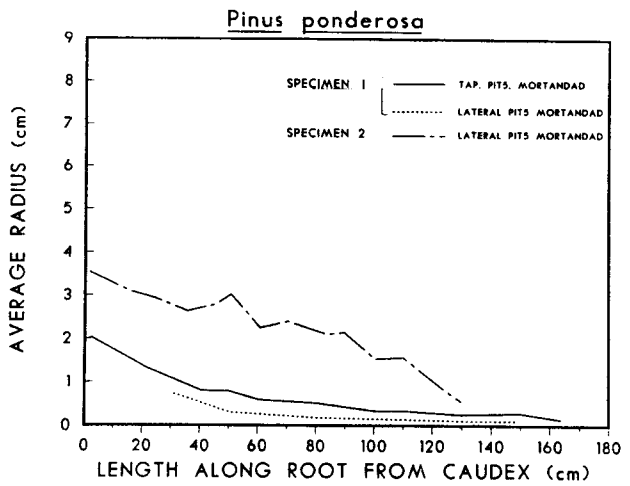
Gross Root Morphology: Outer bark light orange-brown, in thin layers of almost paperlike rectangular plates that curl and become brittle when exposed to air. Inner bark similar to outer bark, but red in color. Wood cream colored. Growth rings and resin ducts usually visible with hand lens, but not visible in our specimens (perhaps because of crude slicing).

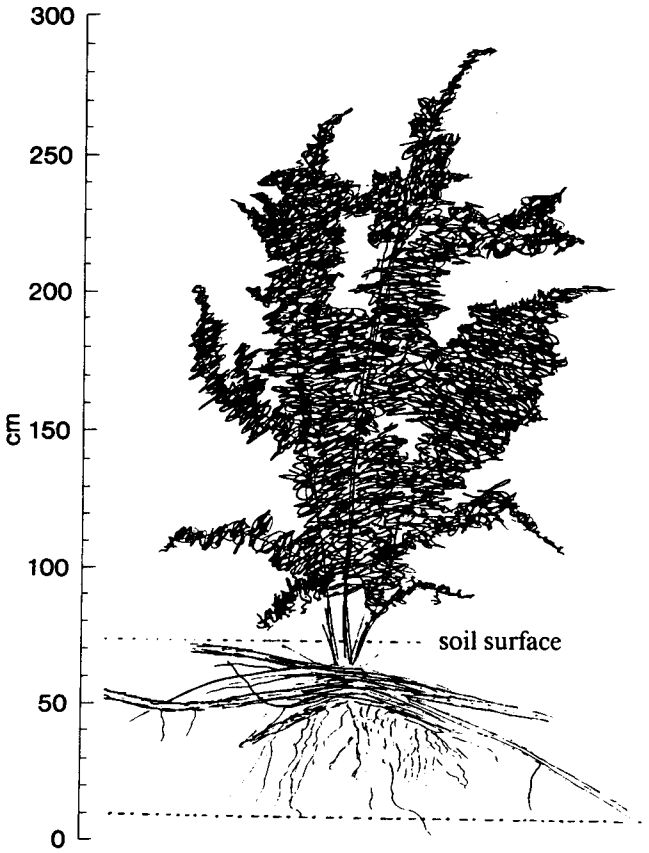
Specimen Age: 8-9 yrs.

Literature: Ponderosa pine may root to 24 m. The average rooting depth is 4 m.

ROOT MEASUREMENTS OF PONDEROSA PINE

Specimen No.	Shoot Height (cm)	Crown Diameter (cm)	Caudex Diameter (cm)	Measured Root Length (cm)	Estimated Maximum Root Length (cm)
1	180	100	4.0	150	160
2	190	80	7.0	130	150





one-seed juniper fruiting branch

One-seed juniper (*Juniperus monosperma*)

Location: One specimen of juniper excavated at Mesita del Buey.

Soils: Clay loam approximately 30 cm deep underlain by tuff.

Habit: Small, broadly pyramidal to globose tree or shrub. Branching from base with upward sweeping limbs.

Plant Description: Much-branched scraggly evergreen tree to 5 meters tall, with yellow-green scalelike leaves. Fruit dark blue to brown with one seed. Bark gray, fibrous, and shreddy. Male and female flowers on separate trees, the female tree producing a berry-like fruit.

Range: Common co-dominant species of the piñon-juniper woodland.

Rooting Habit: Taproots appeared to be vestigial. Most roots were laterals, but some sloped downward and followed cracks in tuff. Other laterals descended until encountering bedrock, then ran along bedrock and soil interface until encountering a fracture. Roots at bedrock were small (2 to 4 mm in diameter).

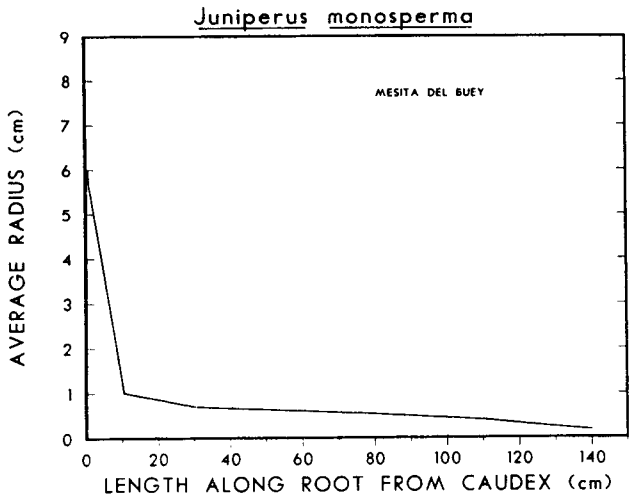
Gross Root Morphology: Outer bark dark red to brown, curling in fibrous, paper-like strips. Inner face of inner bark orange to tan and smooth. Younger roots puncture bark when emerging from wood. Bark, when removed, show root hair holes. Wood uniformly cream colored, but outer wood may be stained by bark.

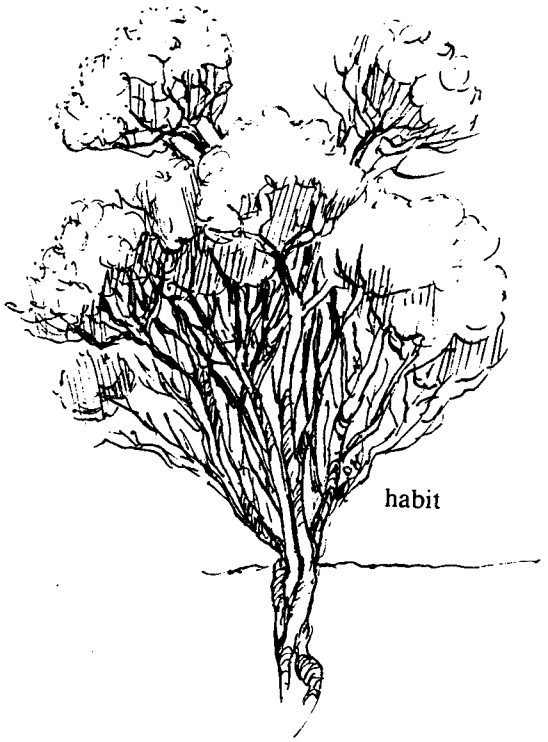
Specimen Age: Not datable.

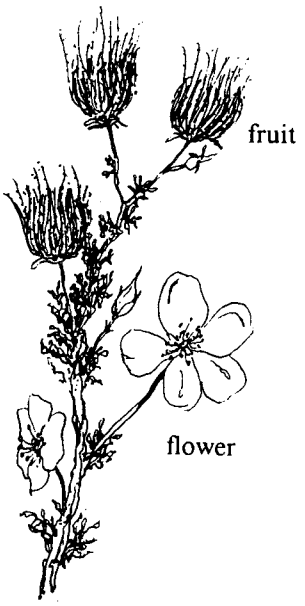
Literature: Maximum rooting depth: 60 m, average rooting depth: 24 m.

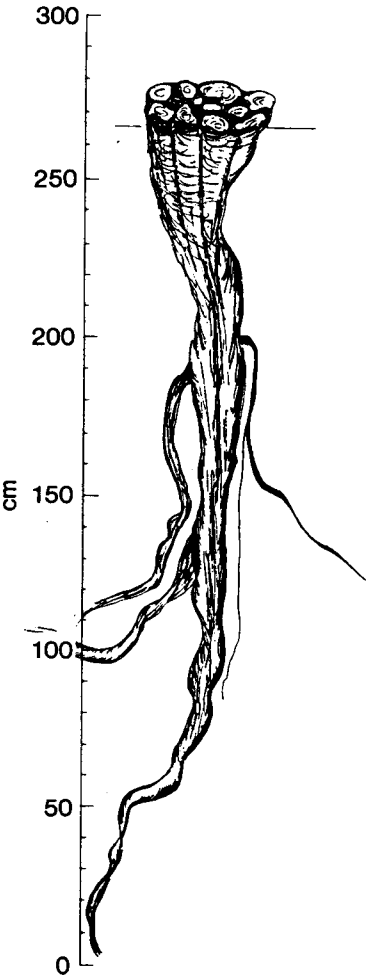
ROOT MEASUREMENTS OF ONE-SEED JUNIPER

Specimen No.	Shoot Height (cm)	Crown Diameter (cm)	Caudex Diameter (cm)	Measured Root Length (cm)	Estimated Maximum Root Length (cm)
1	230	150	6	150	170









Apache plume (*Fallugia paradoxa*)

Location: Three specimens were gathered from Pajarito Canyon.

Soils: Sandy loam interspersed with gravel beds and river cobbles. Sandy loam generally occurs to depths of 60 cm. Below the sand layer, large river cobbles predominate to at least 160 cm.

Habit: Erect stem from caudex or laterals form an irregularly shaped clump or thicket forming shrub.

Plant Description: Leaves wedge-shaped, pinnately divided into three to seven blunt-tipped lobes. Flowers large, white, with three notches at tip of petal. Fruits feathery balls, red-tinged. Blooming and fruiting throughout summer.

Range: Rocky to sandy soils along roadsides and in canyons. This species found on old and relatively new waste sites.

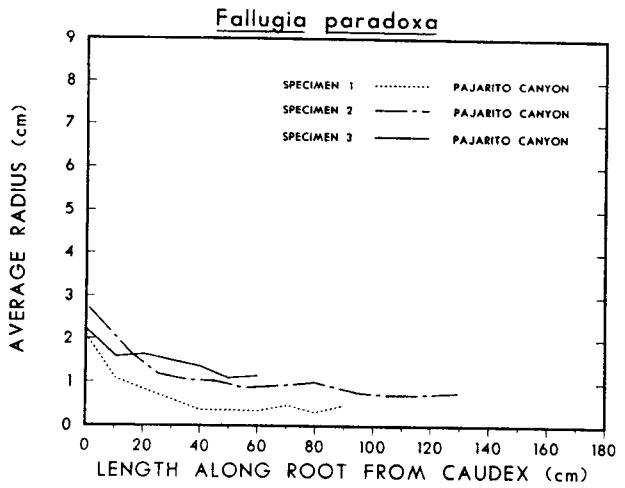
Rooting Habit: Taproot descends directly or is laterally directed. Laterals are frequently shoot-sprouters. Few root hairs or laterals were found within the first 60 cm of taproot length.

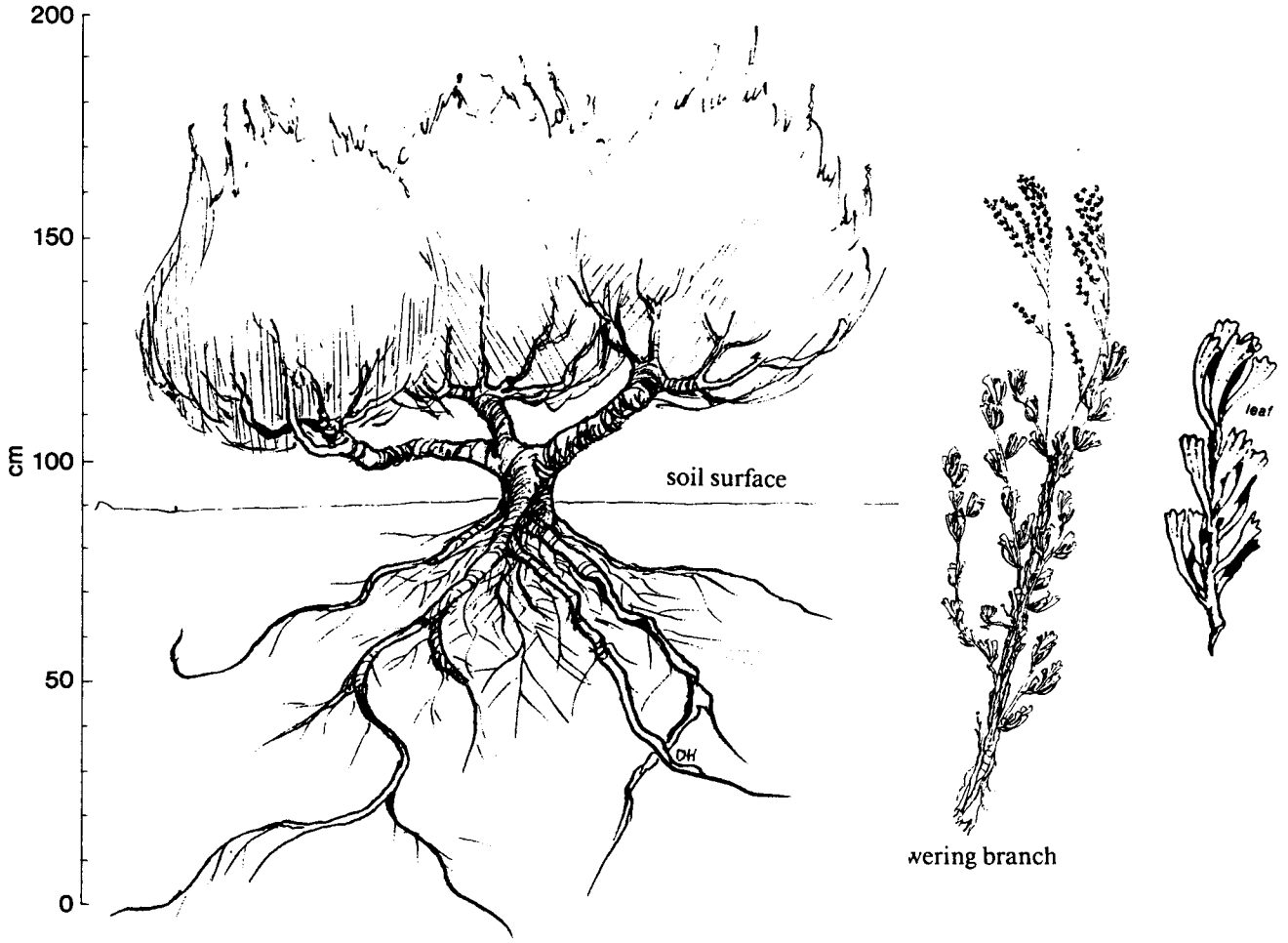
Gross Root Morphology: Roots dark gray. Outer bark on older roots ragged. Bark red to brown on upper sections, becoming more red in color on lower sections. Reddish bark bitter tasting and peeling off in long, thick strips approximately 1 cm wide; inner wood pale yellow. Growth rings sometimes evident with hand lens. Rings differentiated by minute, pore-like holes arranged concentrically.

Literature: No rooting values found.

ROOT MEASUREMENT OF APACHE PLUME

Specimen No.	Shoot Height (cm)	Crown Diameter (cm)	Caudex Diameter (cm)	Measured Root Length (cm)	Estimated Maximum Root Length (cm)
1	88	65.0	4.0	90	170
2	165	2.0	5.5	130	290
3	---	65.5	5.0	60	260





Big sagebrush (*Artemisia tridentata*)

Location: Four specimens of big sagebrush were excavated: two in Potrillo Canyon (1 and 2), and two in Pajarito Canyon (3 and 4).

Soils: Soils in Potrillo Canyon were a sandy loam, about 1.5 m deep, underlain by coarse sand and pumice. Soils in Pajarito Canyon were a sandy loam to 60 cm underlain by large river cobbles to at least 160 cm.

Habit: Irregular, many branched, sometimes flat topped shrub. Branching from a single thick stem. Lower stem often branchless in older specimens.

Plant Description: Strong-smelling shrub to 122 cm. Young stems hairy, older stems with shreddy bark. Very small flowers in heads arranged in long sprays.

Range: Thrives best in alkaline-free soils throughout the piñon-juniper woodland and sometimes into the ponderosa pine forests, particularly on disturbed sites such as archeological ruins.

Rooting Habit: Sagebrush has a massive awl-shaped top root extending from the caudex. In our specimens, the taproot usually divided 9 to 13 cm along the length into one or more laterals. Immediately below the caudex there were amassed, fine (1 to 3 mm diameter) lateral rootlets; these appeared sparsely on all major roots but are most numerous just below the caudex.

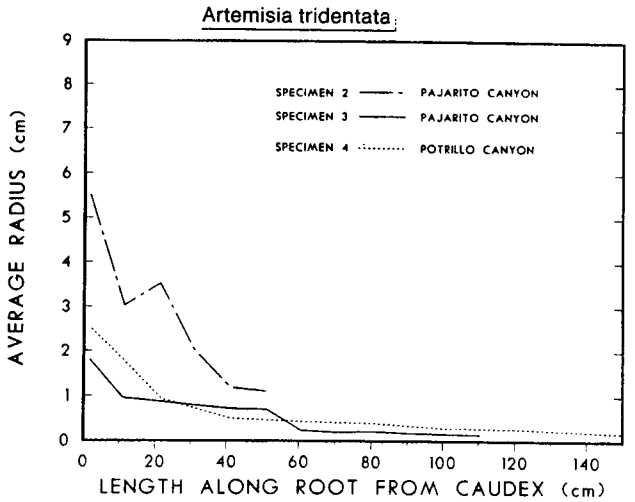
Gross Root Morphology: Fresh outer bark reddish-tan, shredding easily into long (1 m) hair-like or thin strips easily mistaken for shredded juniper bark. After drying, outer bark becoming dark, dull gray. Outer wood cream colored; inner wood light brown. Growth rings evident even without use of a hand lens.

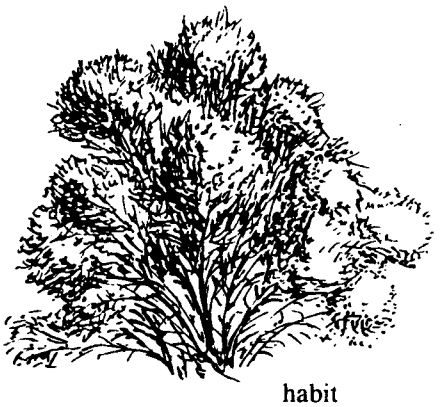
Specimen Age: Appear to be from 7-19 yrs.

Literature: Maximum rooting depth: 914 cm, average rooting depth 248 cm.

ROOT MEASUREMENTS FOR BIG SAGEBRUSH

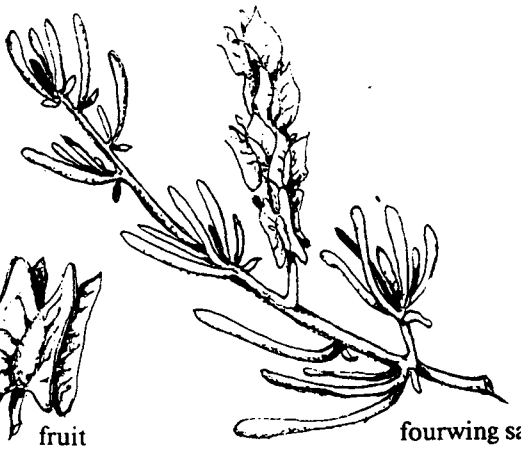
Specimen No.	Shoot Height (cm)	Crown Diameter (cm)	Caudex Diameter (cm)	Measured Root Length (cm)	Estimated Maximum Root Length (cm)
1	84	50	---	10 (broken)	---
2	166	100	11.0	40 (broken)	---
3	45	35	3.5	110	130
4	80	65	5.0	150	180



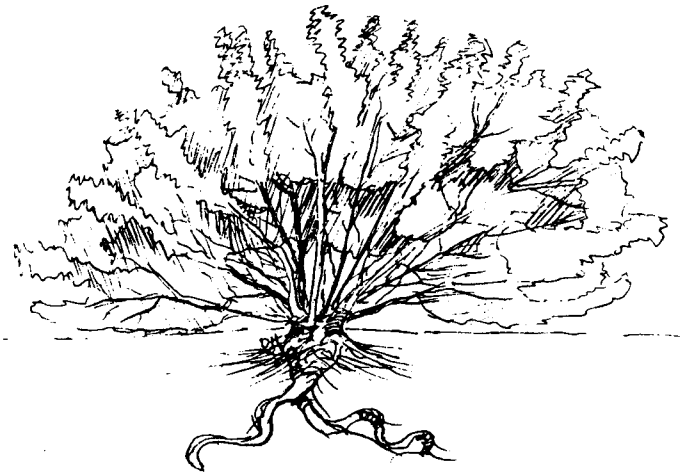


habit

fruit



fourwing saltbush fruiting branch



Fourwing saltbush (*Atriplex canescens*)

Location: Two specimens of this shrub were collected from Mesita del Buey.

Soils: Clay loam underlain by tuff.

Habit: Mounded, woody shrub.

Plant Description: Shrub to 1.5 m tall. Gray-green leaves attached directly to the stem. Branches covered with gray scale-like particles. Flowers light yellow; male and female flowers on different plants. Fruit with four winged bract.

Range: Characteristically a shrub of alkaline or saline soils. Found in rocky areas of canyons and lower mesas. Common to disturbed areas particularly archeological ruins.

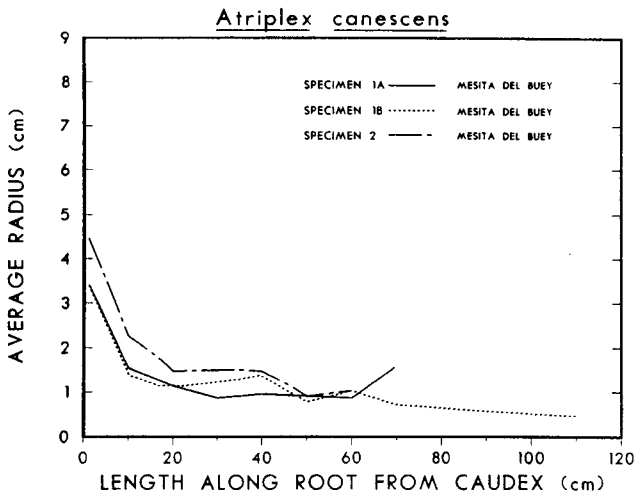
Rooting Habit: Numerous (60 to 100), small (1 to 4 mm diameter) lateral roots emerged just below the caudex; below this cluster was a tap root dividing once or twice into secondary roots; these secondary roots tending to curl or twist, showing a thickening at the points of maximum curvature. The longer secondary roots may enter cracks or fissures in bedrock; root divisions tend to occur on contact with bedrock.

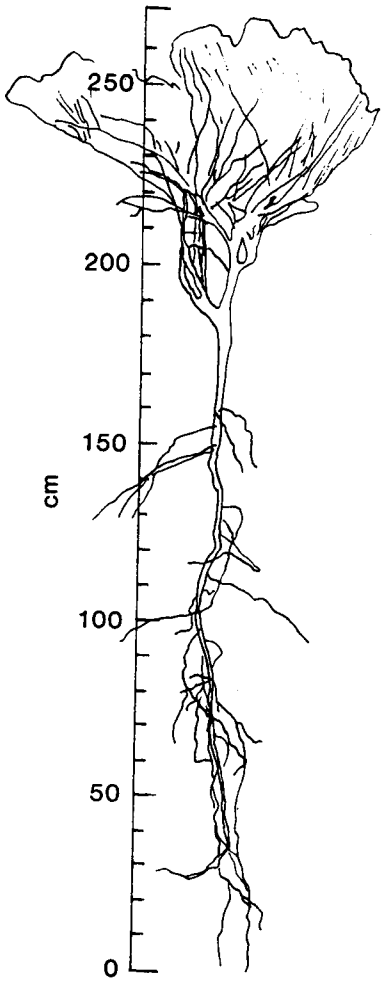
Gross Root Morphology: The large woody roots oval in cross section; outer bark dull, dusty brown, smooth, with tiny disconnected grooves; outer bark very thin and adhering to cream colored inner wood. Growth rings separated by spacing when dry.

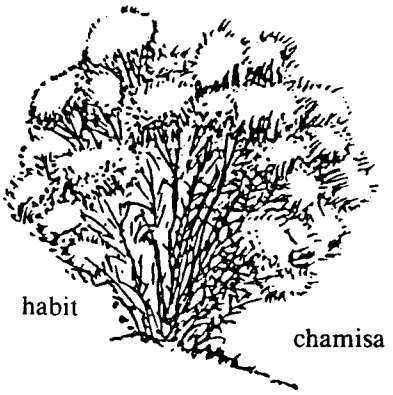
Literature: Maximum rooting depth: 7.6 m, average rooting depth: 314 cm.

ROOT MEASUREMENTS OF SALTBUSH

Specimen No.	Shoot Height (cm)	Crown Diameter (cm)	Caudex Diameter (cm)	Measured Root Length (cm)	Estimated Maximum Root Length (cm)
1	140	220	7	1A - 70 1B - 110	1A - 185
2	250	230	9	60 (broken)	220







Chamisa, Rubber rabbitbrush (*Chrysothamnus nauseosus*)

Location: Three specimens of chamisa were excavated in Mortandad Canyon, Site 1.

Soils: Alluvial, deep sandy loam.

Habit: From base of shrub, several erect stems with clumps of flowering heads form a mounded crown.

Plant Description: Shrub growing 91 to 243.8 cm. Bark shreddy, twigs with matted hairs. Leaves alternate, narrow 2 to 8 cm long; margins smooth, surfaces densely hairy. Flowers in heads at ends of stems, yellow. Flower heads showy, but each individual flower small; no ray flowers present.

Range: Pioneer along roadsides and in disturbed areas, sometimes growing in thickets. Piñon-juniper woodland.

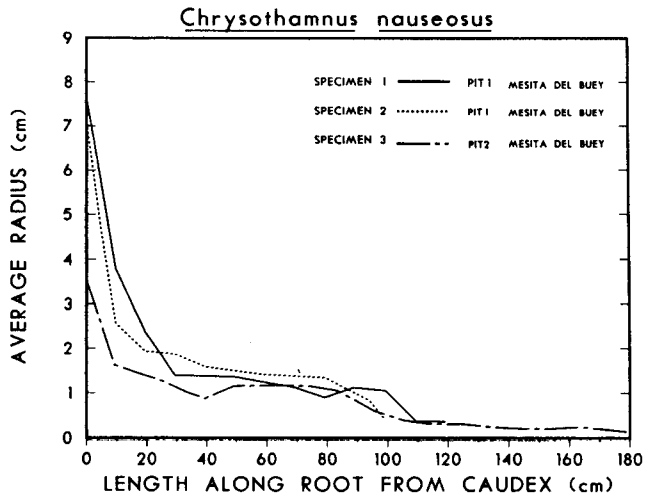
Rooting Habit: Taproot twisted, dividing several times into twisted laterals. Laterals descending a few feet away from caudex.

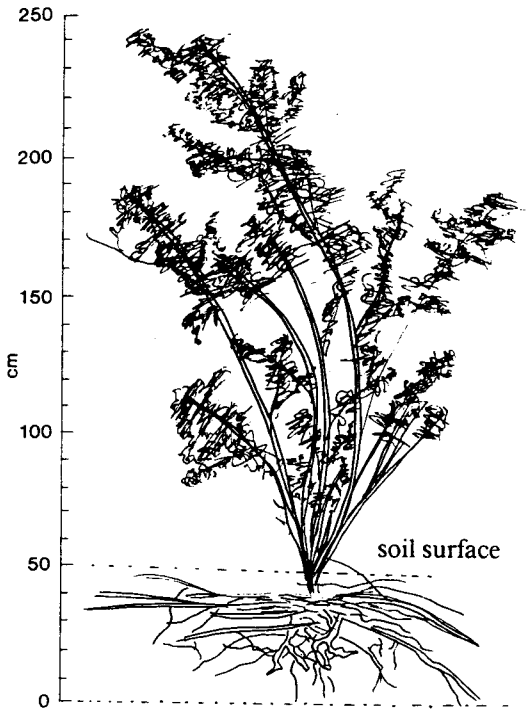
Gross Root Morphology: Outer bark buff to gray-brown with a faint, irregular reticulate pattern; inner bark light brown to buff. Wood cream colored, fibrous. Amber resin crystals on inner surface of inner bark. Roots in cross section scallop-shaped as a result of twisting. Growth rings visible with hand lens when fresh and clearly differentiated when dry.

Literature: Maximum rooting depth: 4.5 m, average rooting depth: 1.5 m.

ROOT MEASUREMENTS OF CHAMISA

Specimen No.	Foliage Height (cm)	Foliage diameter (cm)	Caudex Diameter (cm)	Measured Root Length (cm)	Estimated Maximum Root Length (cm)
1	140	120	14	100	140
2	110	70	15	120	180
3	140	130	7	180	210





Mountain mahogany (*Cercocarpus montanus*)

Location: One specimen excavated on Mesita del Buey.

Soils: Soils generally shallow and rocky except in isolated pockets and basins. Soils only approximately 30 cm deep underlain by tuff.

Habit: Irregularly shaped shrub with erect branching from base.

Plant Description: Erect, spreading shrub growing to 2 m tall; most conspicuous when in fruit. Fruit long-tailed, corkscrew-shaped. Twigs covered with waxy hairs, which are lost as twig matures. Leaves oval-shaped, either alternate or in close bundles, margins toothed. Flower inconspicuous, greenish, 1 to 3 per leaf axil.

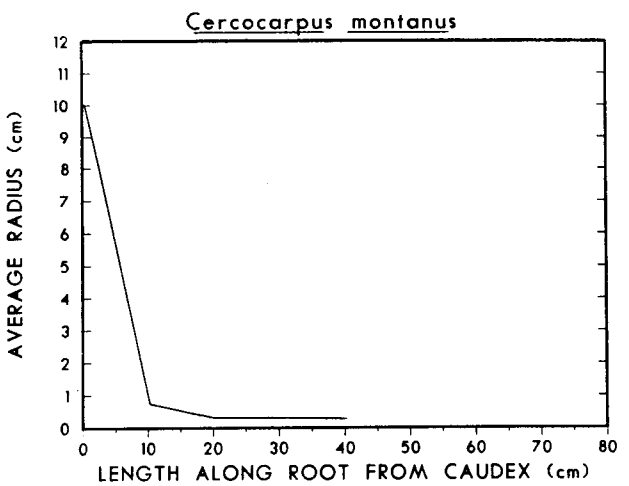
Root Habit: There were no well-defined main taproots; but several laterals radiated from the caudex; small-diameter laterals entered cracks in bedrock. Many fine roots (<1 mm diameter) were found between the caudex and larger laterals. Fine roots were observed descending into cracks in tuff at about 60 cm. Some fine laterals extended as far as 2 m before descending into cracks.

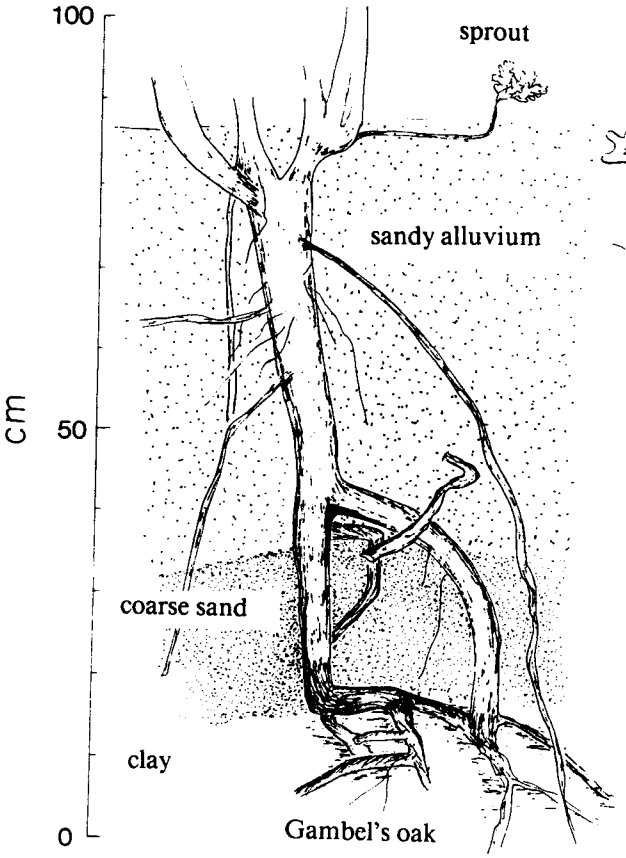
Gross Root Morphology: Roots rigid; outer bark hard, almost black, rough in appearance with longitudinal striations along which fractures occur. Outer bark not peeling easily. Inner bark red with shallow and discontinuous grooves. Outer wood surface shallowly striated with grooves and ridges running the entire length of root. Inner wood cream colored with no visible growth rings.

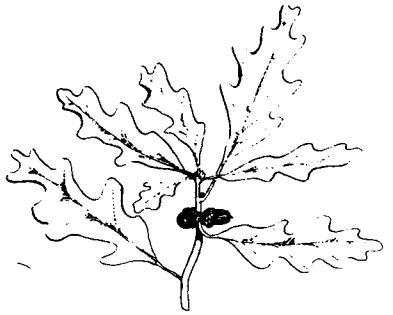
Literature: Average rooting depth, 113 cm; the range was 40 to 152 cm.

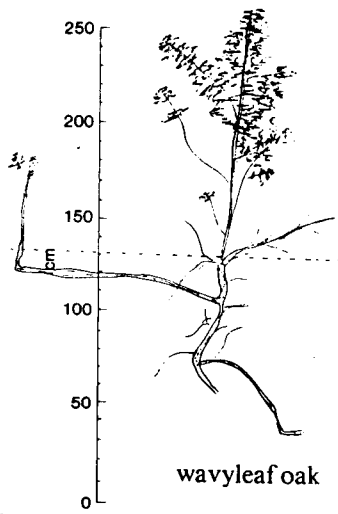
ROOT MEASUREMENTS OF MOUNTAIN MAHOGANY

Specimen No.	Shoot Height (cm)	Crown Diameter (cm)	Caudex Diameter (cm)	Measured Root Length (cm)	Estimated Maximum Root Length (cm)
1	180	120	20	40 (broken	50









Oak (*Quercus spp.*)

Location: Three specimens of oak were gathered at Mesita del Buey (2-4) and one was excavated in Mortandad Canyon.

Soils: Soils on Mesita del Buey were approximately 30 cm deep underlain by tuff. Soils in Mortandad Canyon were sandy loamy alluvium.

Habit: Shrub or small tree in groves or thickets.

Plant Description: Gambel Oak (*Quercus gambelii):* Shrubs growing to 30 m. Leaves lobed with lobes more than halfway to the midrib vein. Leaves bright green above, sometimes velvety-hairy below.

Wavyleaf Oak (*Quercus undulata*): Shrubs growing to 2 m tall. Leaf margins smooth or wavy, cut no more than one-fourth the way to the midrib vein. Leaves blue-green with starshaped hairs on the underside.

Note: These shrubs easily hybridize where their ranges overlap.

Range: Gambel oak is most commonly found in the ponderosa pine and mixed conifer forests. Wavyleaf oak is more commonly found in the piñon-juniper woodland, sometimes in the ponderosa pine forest.

Rooting Habit: Generally one large tap root branched into laterals at about 25 cm depth; laterals from the caudex descend or extend horizontally, sending up shoots within a meter or so of the branch point (this is why "oak thickets" occur). Several large, woody stems emerged from the buried caudex. Roots of Gambel's oak appeared more robust and deeply penetrating than those of the wavyleaf oak.

Gross Root Morphology: Roots highly variable. In general, outer bark reddish brown, thin, patchy, reticulate with raised circular scars from root buds (sometimes puncture holes from root hairs instead of scars). Inner bark thin, yellow-brown in color, parchment-like in texture, and adherring to outer wood. Outer wood fibrous, usually cream colored, but sometimes stained yellow-brown by bark. Inner wood white, sometimes showing a dark center.

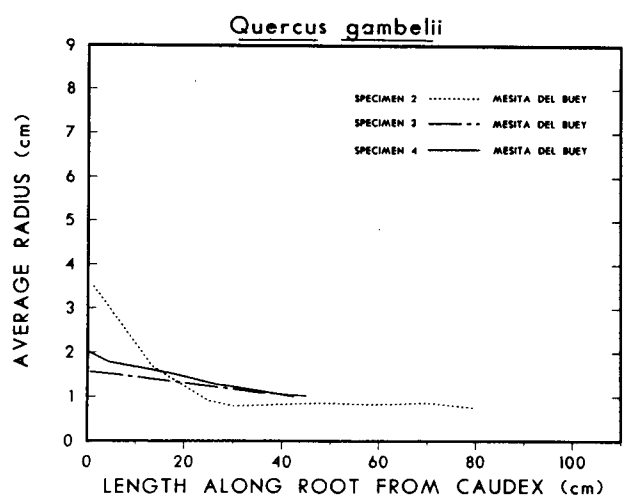
Specimen Age: 40-50 years.

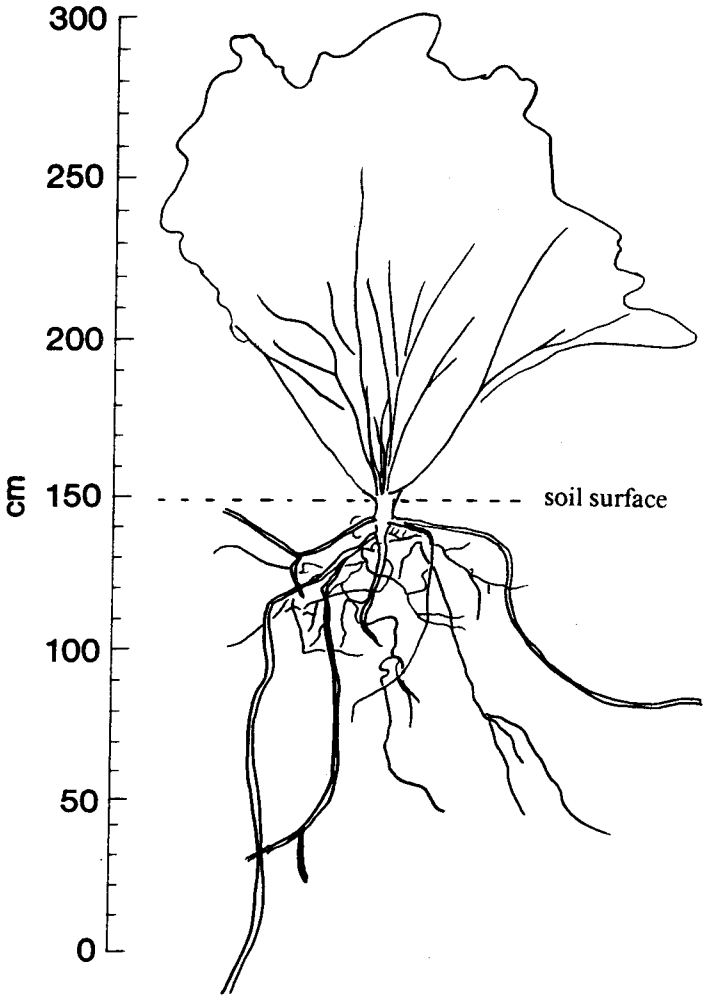
Literature: Maximum rooting depth: 4 m, average rooting depth: 238 cm.

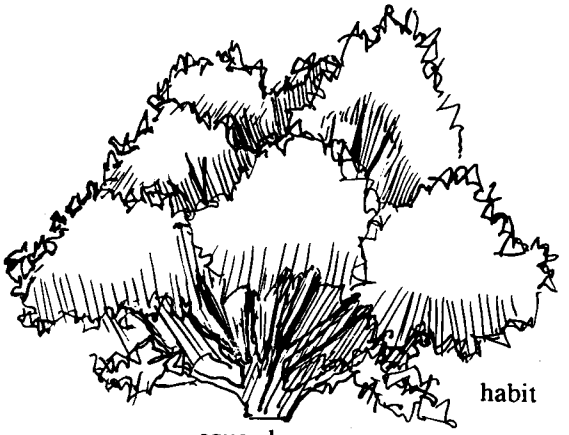
ROOT MEASUREMENTS OF OAK

Specimen No.	Shoot Height (cm)	Crown Diameter (cm)	Caudex Diameter (cm)	Measured Root Length (cm)	Estimated Maximum Root Length (cm)
1 [a]	210	220	10.7	100	---
2	116	117	7.0	80	320
3	116	88	3.2	50	150
4	130	127	4.0	45	175

[a]Specimens 1 and 2, Gambel oak (*Q. gambelii*).
Specimens 3 and 4, wavyleaf oak (*Q. undulata*).







Squawberry (*Rhus trilobata*)

Location: Two specimens were excavated in Mortandad Canyon, Site 2.

Soils: Loamy sand to a depth of 30 cm, followed by dense clay, hardpan, and finally a coarse sand to indefinite depths.

Habit: A large, mounded shrub with dense, stiff, sometimes spiny branching.

Plant Description: Shrub growing 91 cm to 3 m, often in thickets. Leaves compound with 3 leaflets. Fruit orange-red.

Range: Deep soils of canyons and mesas, mainly piñon-juniper woodland.

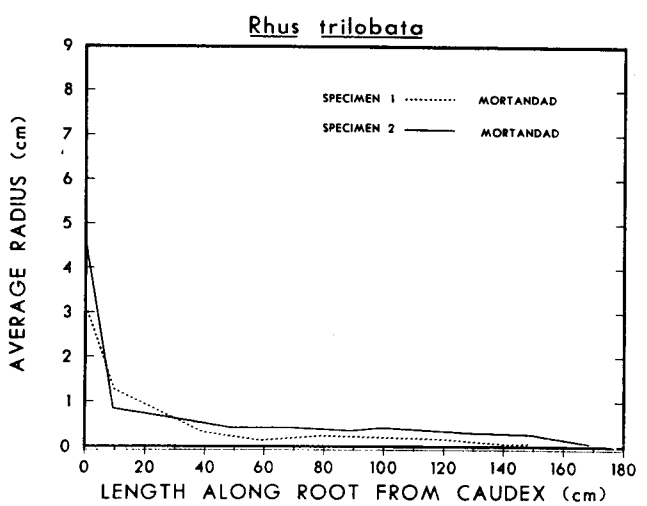
Rooting Habit: All root laterals came from just below the caudex and branched profusely. Laterals were all about the same length. A tap-like root descended 10 cm below caudex.

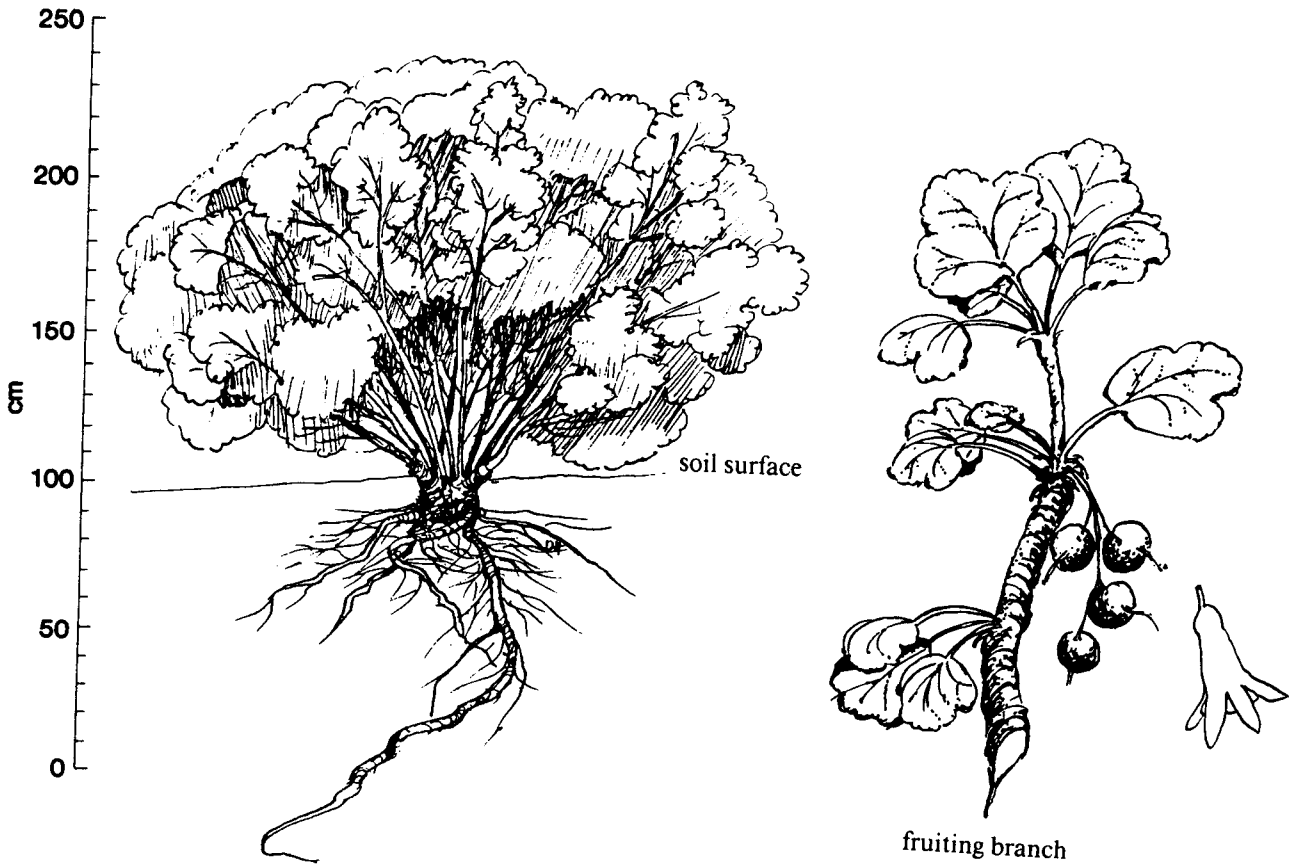
Gross Root Morphology: Outer bark medium to dark brown, easily peeled when damaged. Transverse fractures evident after exposure to air. These fractures first appearing to be rust-colored lenticels, but are actually an exposed rust-brown inner layer of outer bark. Innermost layer of outer bark pale green, very sticky; inner bark white. Cells of growth rings evident with hand lens; each ring of dense cells separated by a ring of pore-like holes. Sticky exudent when fresh.

Literature: No literature values found.

ROOT MEASUREMENTS OF SQUAWBERRY

Specimen No.	Shoot Height (cm)	Crown Diameter (cm)	Caudex Diameter (cm)	Measured Root Length (cm)	Estimated Maximum Root Length (cm)
1	140	90	6	150	210
2	180	180	9	170	230





Wax currant (*Ribes cereum*)

Location: Three specimens of wax currant were excavated: two in Mortandad Canyon (1 and 2) and one (3) at Mesita del Buey.

Soils: Soils in Mortandad Canyon were alluvial, sandy loam. Soils on Mesita del Buey were clay loam approximately 91 cm deep underlain by a tuff.

Habit: Rounded, densely branched shrub.

Plant Description: Thicket-forming shrub growing to 3 m. Leaves palmately veined and lobed, circular to kidney-shaped. Flowers tubular, pink to white. Fruits red.

Range: In canyons and on mountain slopes. Invaders of roadsides and disturbed areas.

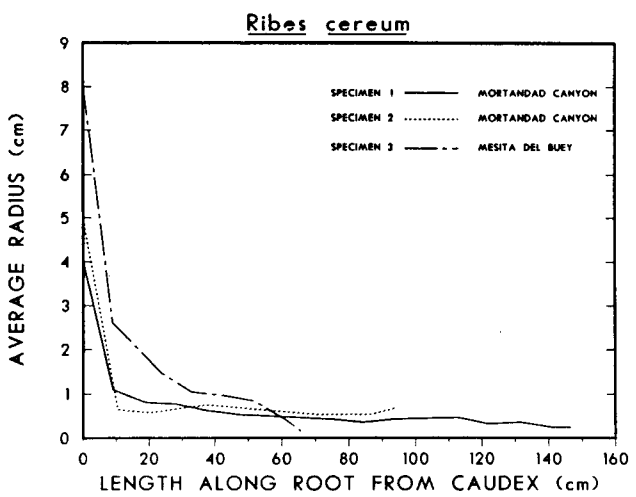
Rooting Habit: Caudex of the wax currant was massive. The main roots were laterals emerging radially from lower parts of the caudex, then sloping downward at about 30 cm from the caudex axis. Hundreds of hair-like roots (1 mm diameter or less) were massed at the caudex and on main roots to a distance of about 10 cm from the axis.

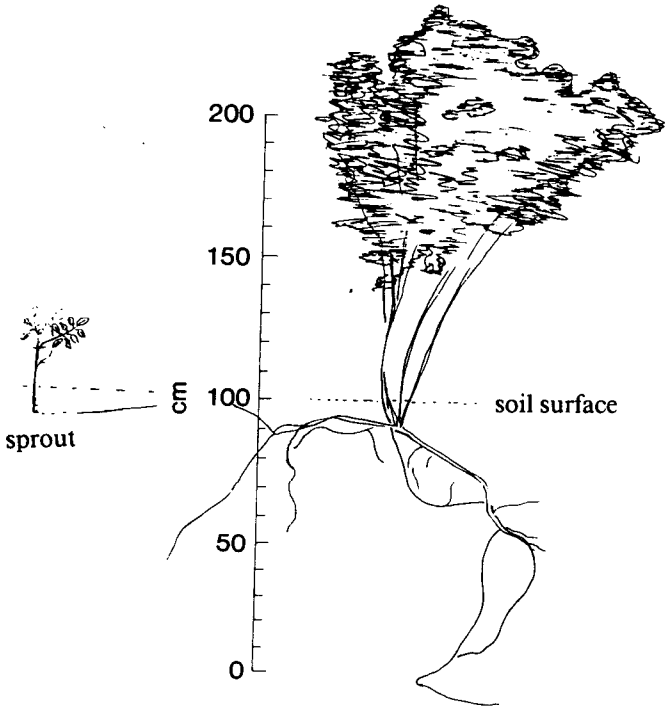
Gross Root Morphology: Outer bark reddish-brown with fractures perpendicular to axis of root (instead of parallel, that is, longitudinal fractures, as in most other roots). Inner bark wine colored with white or deep red lenticles. Outer wood vitreous with short, raised disconnected striations. Inner wood white with no evidence of growth rings.

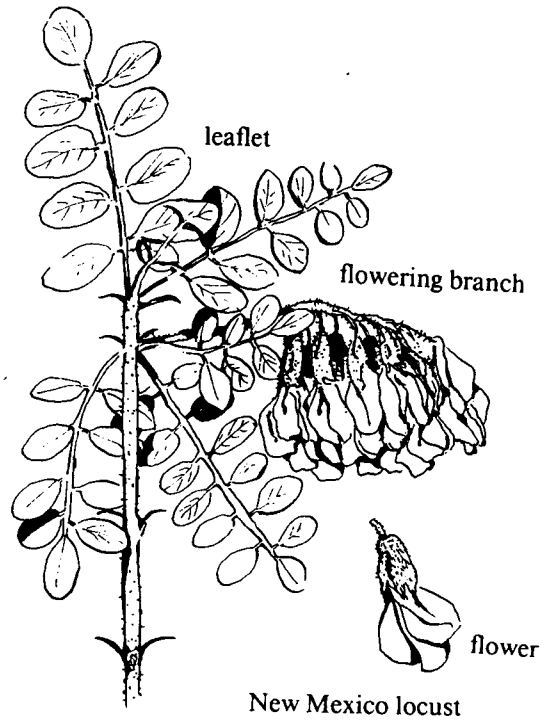
Literature: No values found.

ROOT MEASUREMENTS OF WAX CURRANT

Specimen No.	Shoot Height (cm)	Crown Diameter (cm)	Caudex Diameter (cm)	Measured Root Length (cm)	Estimated Maximum Root Length (cm)
1	160	150	8	150	290
2	120	100	10	100 (broken)	---
3	186	203	16	70 (broken)	80







New Mexico Locust (*Robinia neomexicana*)

Location: Two specimens of this shrub were excavated in Mortandad Canyon.

Soils: Alluvial, sandy loam.

Habit: Erect, thorny shrub or small tree. Often forming thickets.

Plant Description: Here, thicket-forming shrubs growing to 8 m. Branches with straight or curved spines. Leaves pinnately compound, blue-green, somewhat hairy. Flowers rose-pink.

Range: Canyons, along roadsides of the piñon-juniper woodland and ponderosa pine forest.

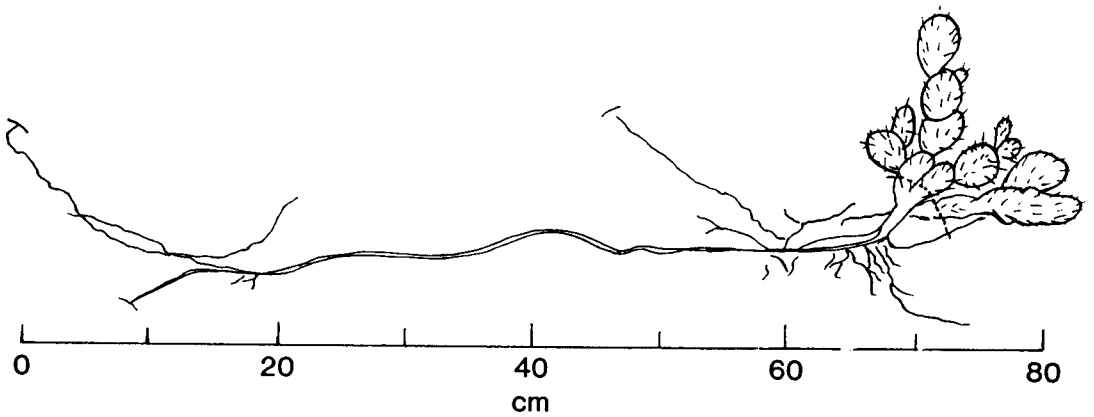
Rooting Habit: Roots near the surface with lateral roots forming new shoots.

Gross Root Morphology: Outer bark reddish brown, thin and soft. Easily rubbed or peeled off in thin flakes to show fine striations on inner surface. Inner bark is cream colored with fine fibers appearing on broken edges. Outer wood white; inner wood light brown, appearing porous under a hand lens.

Literature: No values found.

ROOT MEASUREMENT OF NEW MEXICO LOCUST

Specimen No.	Shoot Height (cm)	Crown Diameter (cm)	Caudex Diameter (cm)	Measured Root Length (cm)
1	190	53	7	140
2	180	120	10	100



Prickly pear (*Opuntia polyacantha*)

Location: Three specimens were collected from Mortandad Canyon and one from Mesita del Buey.

Soils: Soils in Mortandad Canyon were alluvial sandy loam. Soils on Mesita del Buey, clay loam.

Habit: Fleshy, flattened stems (pads) spreading in clumps.

Plant Description: Cactus about 15 cm tall. Joints circular to oval, to 10 cm long. Spines 6 to 10 per areole, downward-slanting. Flowers yellow. Fruit about 1.5 cm in diameter, dry, brown, and very spiney.

Range: Piñon-juniper woodland; dry rocky canyons and mesas. Often found on disturbed, overgrazed or sheet washed sites.

Rooting Habit: Roots of specimens collected were in soft sand or clay loam with no noticeable obstructions below them. All roots appeared to be laterals, <3 mm in diameter; clustered below and connected with one or two pads.

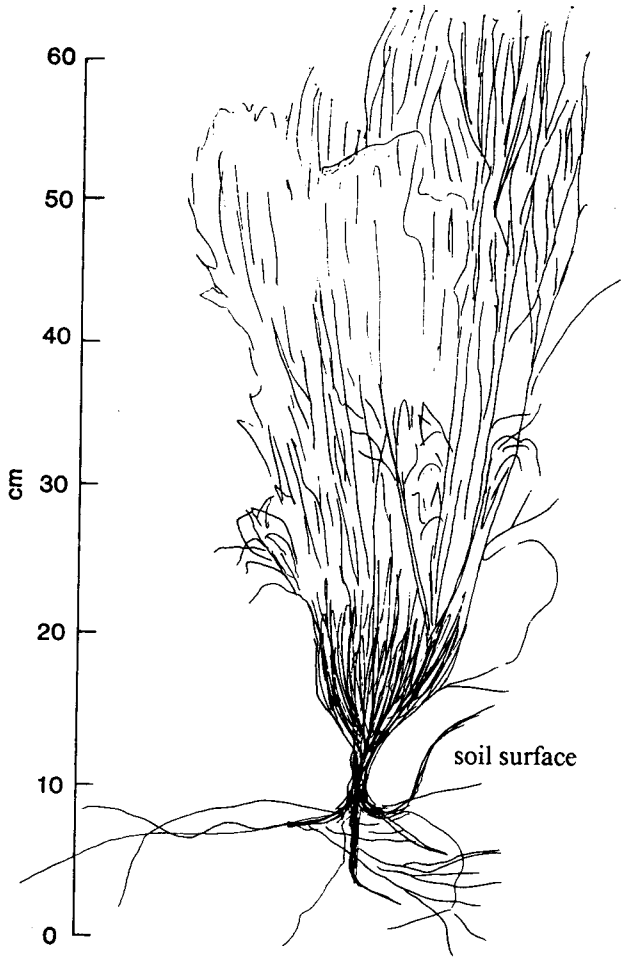
The prickly pear propagates mainly by roots lying a few centimeters under the surface; some of these roots can be as much as 1.5 m long. The root zone for the specimens we observed was no deeper than 4 cm.

Gross Root Morphology: Roots uniformly cream colored and rounded, emerging from a stem-like rooting part under pads.

Literature: Maximum rooting depth: 366 cm; average rooting depth 76.5 cm.

MEASUREMENTS OF CACTI

Specimen No.	Shoot Height (cm)	Cluster Dimensions (cm)	Measured Root Length (cm)
1	15	35 × 40	28 (<3 mm diam)
2	22	30 × 6	10 (<1 mm diam)
3	10	5 × 12	8 (<2 mm diam)



Pinque (*Hymenoxys richardsonii*)

Location: One specimen excavated in Mortandad Canyon and one in Mesita del Buey.

Soils: At the excavation sites, Mortandad Canyon soils were sandy loam while those of Mesita del Buey were clay loams.

Habit: Perennial forb; several woody stems near base branching near top into a slightly mounded or flat top shape.

Plant Description: Growing to 45 cm tall. Flowers yellow rayed in flat-topped clusters. Leaves divided into 3-7 narrow segments.

Range: Piñon-juniper woodland; invading onto disturbed or overgrazed land.

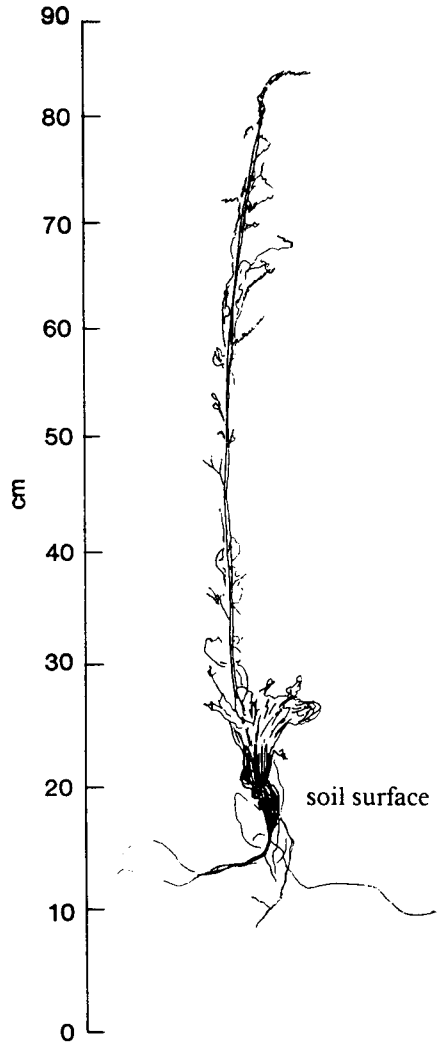
Rooting Habit: Taproot. Our specimens had 3 to 9 partially underground stems; several emerged from the shallow (< cm deep) caudex taproot system. From each of these stems came 2 to 5 herbaceous (aboveground) stems.

Literature: No values found.

ROOT MEASUREMENTS OF PINQUE

Specimen No.	Shoot Height (cm)	Crown Diameter (cm)	Caudex Diameter (cm)	Measured Root Length (cm)
1	36	11	1.5	23 (<4 mm diam)
2	30	21	1.3	25 (<2 mm diam)

(The roots measured were longest laterals in each case.)



habit

Estafiata (*Artemisia frigida*)

Location: Specimens collected in Mortandad and Potrillo Canyon.

Soils: Alluvial, sandy loam.

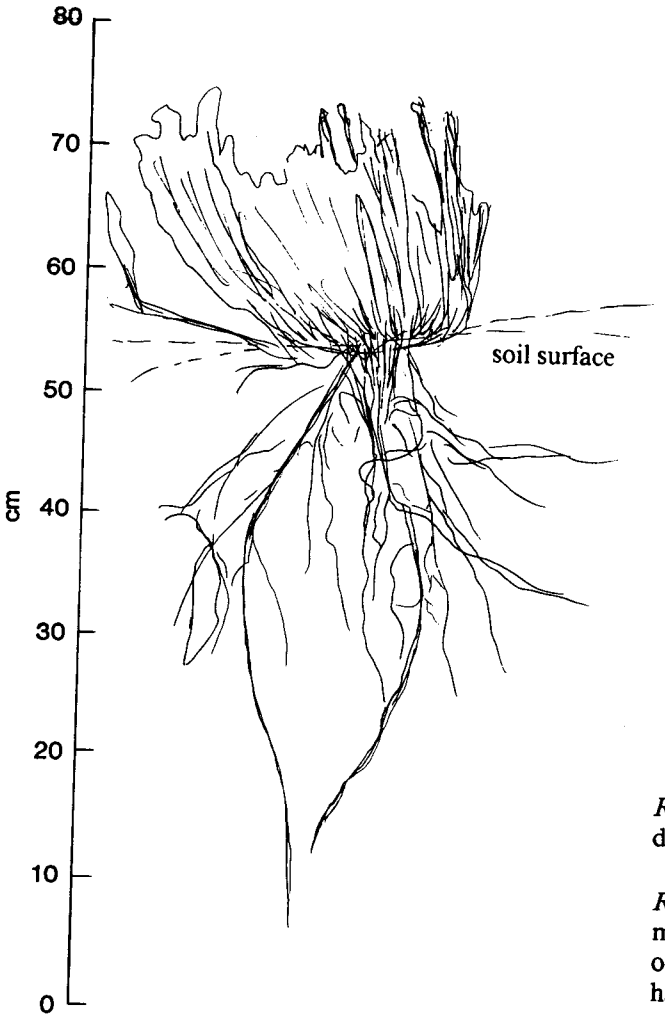
Habit: Perennial herb; often mounded, woody at the base and rooting at prostate stem nodes.

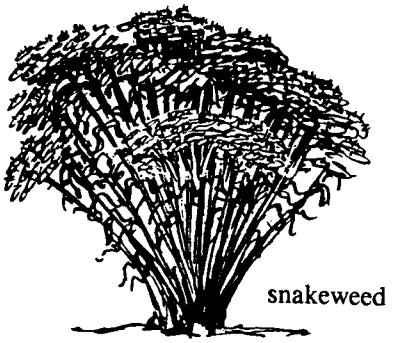
Plant Description: Grows to 45 cm. Stems and leaves covered with short silky hairs. Leaves three times pinnatifid, making them appear feathery. Flowers inconspicuous along raceme.

Range: Throughout the piñon-juniper and ponderosa pine zone. Early invader into abandoned agricultural fields and other disturbed areas.

Root Measurements: Roots of this species and *Artemisia dracunculus* were generally to within 10 cm of the soil surface.

Literature: No values found.





habit

Range: Throughout the piñon-juniper woodland; indicator of overgrazing and other disturbance.

Rooting Habit: All specimens were dug from deep, moist soils; tap roots extended vertically into soil and occasionally branched 1 to 2 cm below caudex. Root hairs were located mostly near caudex.

Literature: Maximum rooting depth: 244 cm, average rooting depth: 122.

Snakeweed (*Gutierrezia sarothrae*)

Location: Three specimens of snakeweed were collected: specimens 1 and 2 were from Mesita del Buey and specimen 3 was from Potrillo Canyon.

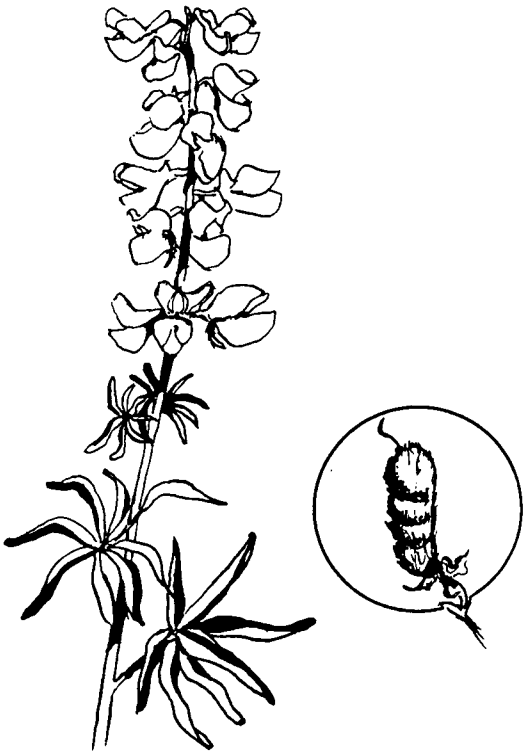
Soils: Clay loam; sandy loam.

Habit: Low growing bushy semishrub; woody at the base.

Plant Description: Subshrub growing to 70 cm. Leaves linear to 7 cm long. Flower heads attached in flat topped clusters. Each flower head with four or five disk flowers. Ray flowers 4 to 6; disk flowers 4 or 5.

ROOT MEASUREMENTS OF SNAKEWEED

Specimen No.	Shoot Height (cm)	Crown Diameter (cm)	Caudex Diameter (cm)	Measured Root Length (cm)
1	46	51	3	34
2	48	52	3	24
3	40	52	2	32



Lupine *(Lupinus caudatus)*

Location: One specimen of lupine was excavated in Mortandad Canyon.

Soils: Alluvial, sandy loam.

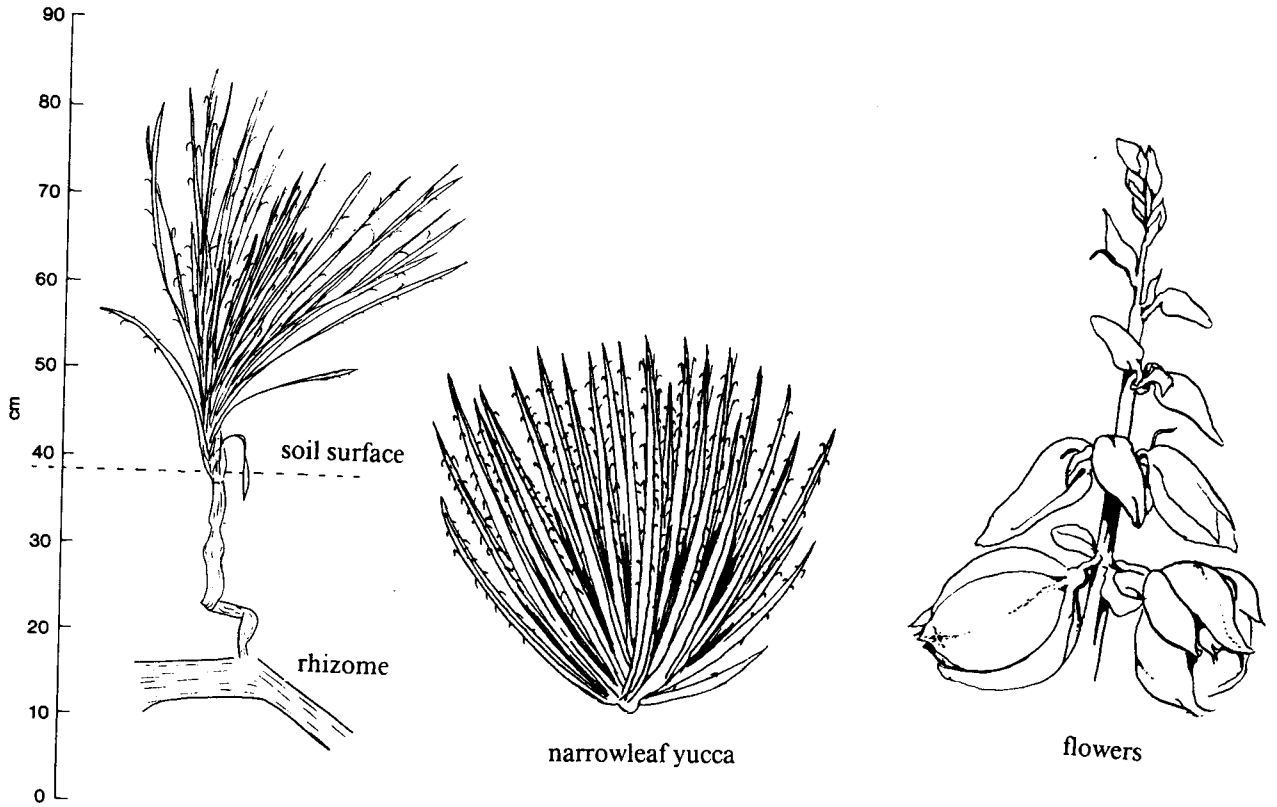
Habit: Perennial herb.

Plant Description: Perennial herb growing to 1 m. Leaflets 7 to 9, long and narrow, wider at the tip than the base; both sides covered with silky hairs. Flowers along the stem in clusters to 25 cm long. Petals dark blue to 1 cm long. Fruit to 3 cm long.

Range: Throughout the piñon-juniper woodland.

Rooting Habit: Specimens excavated were in deep alluvial soils. A single taproot extended vertically into the soil to a depth of greater than 2 m.

Literature: Maximum rooting depth of 240 cm, average rooting depth 182 cm.



Narrowleaf yucca (*Yucca angustissima*)

Location: One rhizome (underground stem) specimen (No. 1) was gathered from a connecting group of four individuals in Mortandad Canyon. A second specimen (No. 2) was retrieved at Mesita del Buey.

Soils: Alluvial, sandy loam.

Habit: Shrub-like perennial herb with leaves clustered near the ground.

Plant Description: Leaves 4-8 mm wide, spine-tipped in large rosettes at base of plant. Flowers on tall stalks, which may or may not extend beyond the leaves. Flowers creamy white to greenish white. Fruits fleshy or dry.

Range: Found throughout the piñon-juniper zone and in disturbed areas of the ponderosa pine zone.

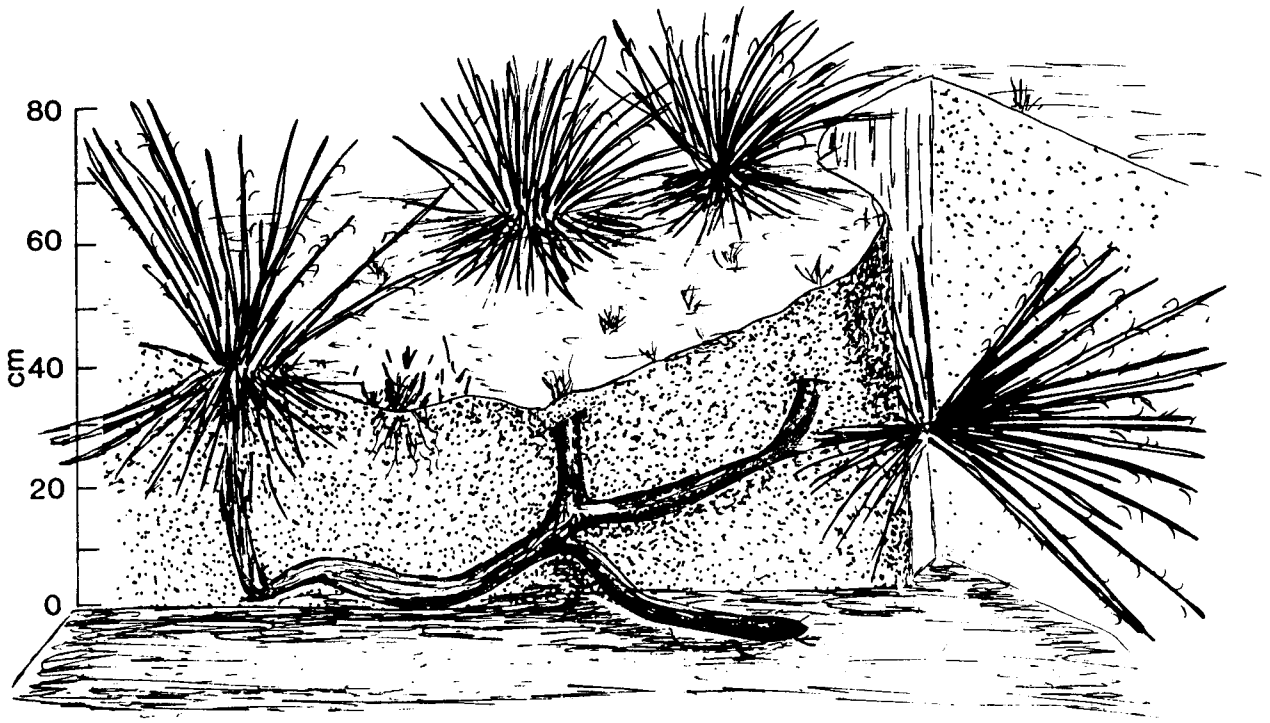
Rooting Habit: Rhizomatous. In our specimens, the main rhizome thick and roughly cylindrical with no evident tapering (about 3.5 cm in diameter specimen 1 and 1.5 cm in diameter in specimen 2). Rhizomes descended approximately 20 cm and then branched horizontally making connections with other individuals in the group. A few short (7 to 10 cm), thin (1 to 2 mm) roots extended laterally from the rhizome. The connecting branch rhizomes all appeared to be about the same thickness as the underground stem, 1.5 to 3.5 cm in diameter. These horizontal underground stems connected different individuals, characteristic of a plant that mainly propagates vegetatively.

Gross Root Morphology: The "bark" of rhizomes is similar in texture to the stems of other monocotyledons (grass or the reeds). Bark is a sheath with fine fringes on the exposed edges where it overlaps. Bark color is rosy red on larger roots, and purple-red on smaller roots; wood is white and pulpy.

Literature: Maximum rooting depth: 244 cm, average rooting depth: 122 cm.

ROOT MEASUREMENTS OF YUCCA

Specimen No.	Shoot Height (cm)	Crown Diameter (cm)	Caudex Diameter (cm)	Measured Root Length (cm)
1	45	65	10	20
2	60	80	21	20



Ecology of rooting patterns of yucca

Mullein (*Verbascum thapsus*)

Location: Two specimens were excavated in Mortandad Canyon.

Soils: Alluvial sandy loam.

Habit: Erect, sturdy, single stemmed biennial forb. Sometimes branching near the top.

Plant Description: Often over 183 cm tall. Stems stout, covered with densely branched, wooly hairs. Stem leaves up to 45 cm long, elliptical to elongate, wider near the tip than the base; margins coarsely toothed. Leaves yellow-green, surfaces covered with branched, wooly hairs. Leaves of the first year very large, in a rosette at the base of the plant. Yellow flowers in a dense, spike-like inflorescence. Petals to 2.5 cm wide, stamens with anthers 5.

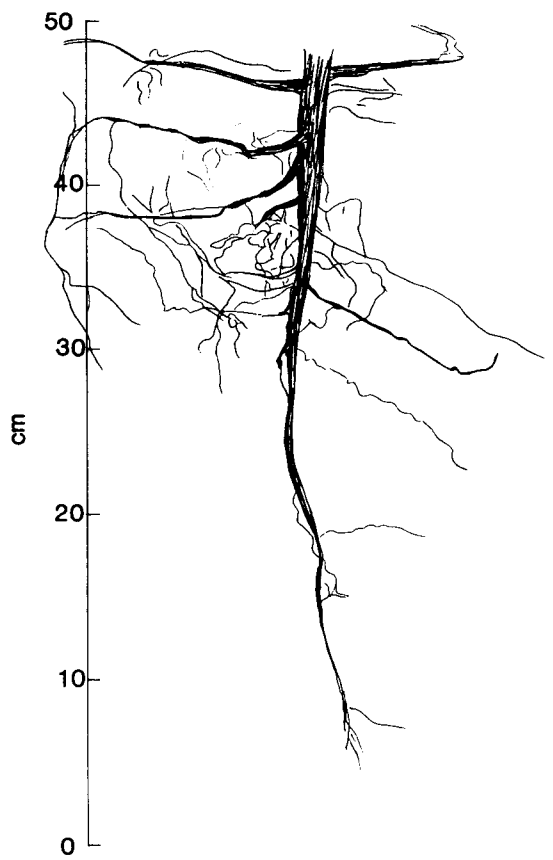
Range: Disturbed soils of the piñon-juniper woodland and ponderosa pine forest.

Rooting Habit: A single, conical taproot with a few short laterals emerging radially.

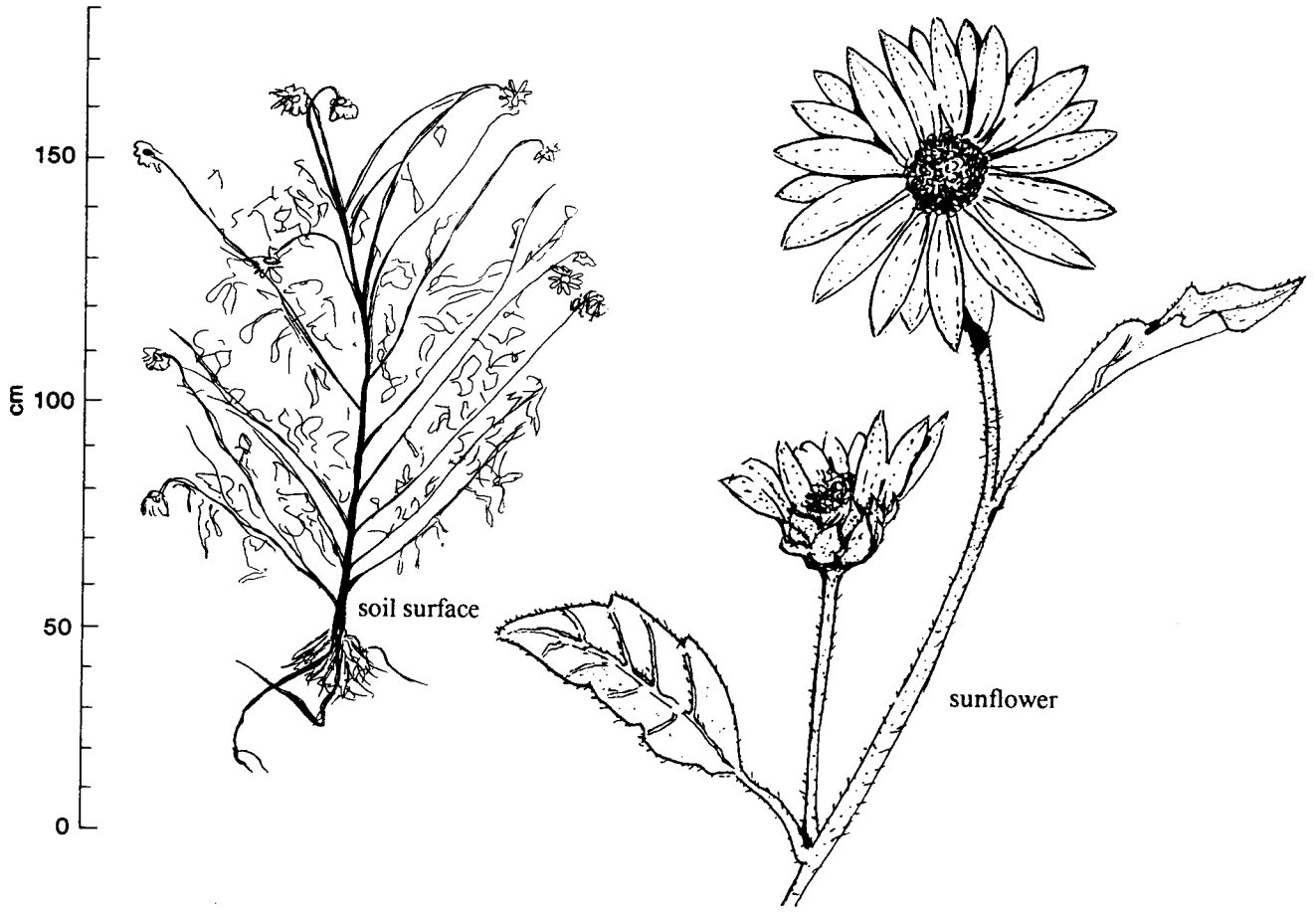
Literature: No values found.

ROOT MEASUREMENTS OF MULLEIN

Specimen No.	Shoot Height (cm)	Caudex Diameter (cm)	Measured Root Length (cm)
1	82	2.0	28
2	97	2.5	42



close-up of rooting pattern in mullein



Sunflower (*Helianthus petiolaris*)

Location: The roots of a single individual of this species were studied on Mesita del Buey; the specimen was removed from a dirt pile by the roadside.

Soil: Dirt pile near roadside, clay loam.

Habit: Erect, alternate branching annual.

Plant Description: Grows to 274 cm tall. Stems hairy. Leaves oval to lance-shaped, coarsely toothed. Flower heads large, rays yellow, 2.5 to 5 cm long. Disk reddish purple, 2 to 5 cm wide.

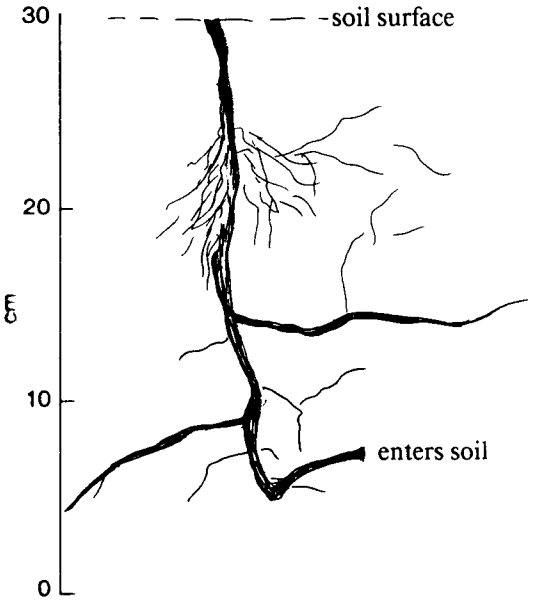
Range: Disturbed soils, roadsides.

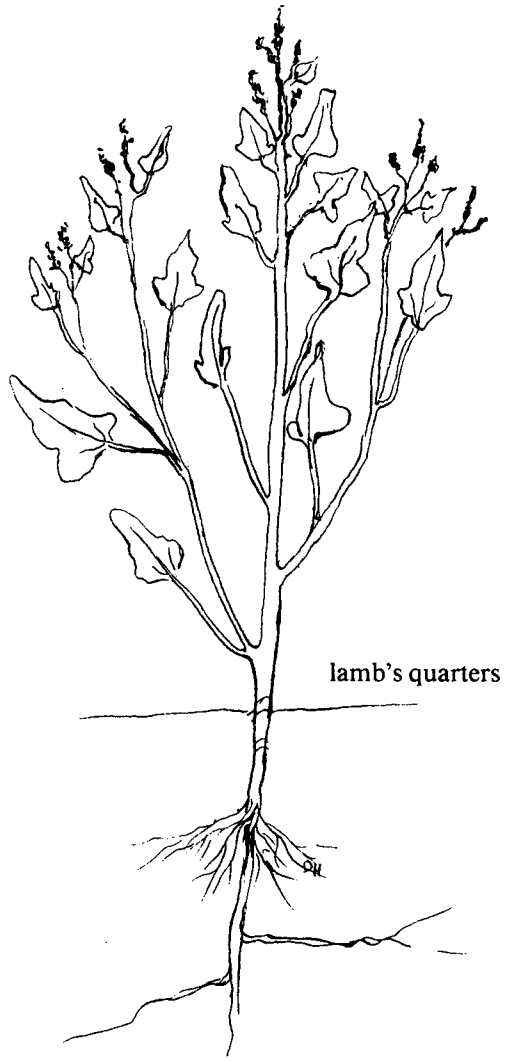
Rooting Habit: Taproot. Five large roots extended to depths of 40 to 45 cm. Each of these main roots was about 1 cm diameter. Masses of hairlike roots were attached to each main root and appeared to extend radially to distances of at least 20 cm.

Literature: No values found.

ROOT MEASUREMENTS OF SUNFLOWER

Height (cm)	Crown Diameter (cm)	Caudex Diameter (cm)	Measured Root Length (cm)
120	120	4	45





Fremont's goosefoot (*Chenopodium fremontii*)

Location: One specimen of this annual herb was examined on Mesa del Buey.

Soils: Large dirt stockpile, clay loam.

Habit: Bushy annual.

Plant Description: Annual forb growing to 80 cm. Leaves triangular to diamond shaped, bright green. Flowers greenish, arranged in crowded clusters at tip of stem branches.

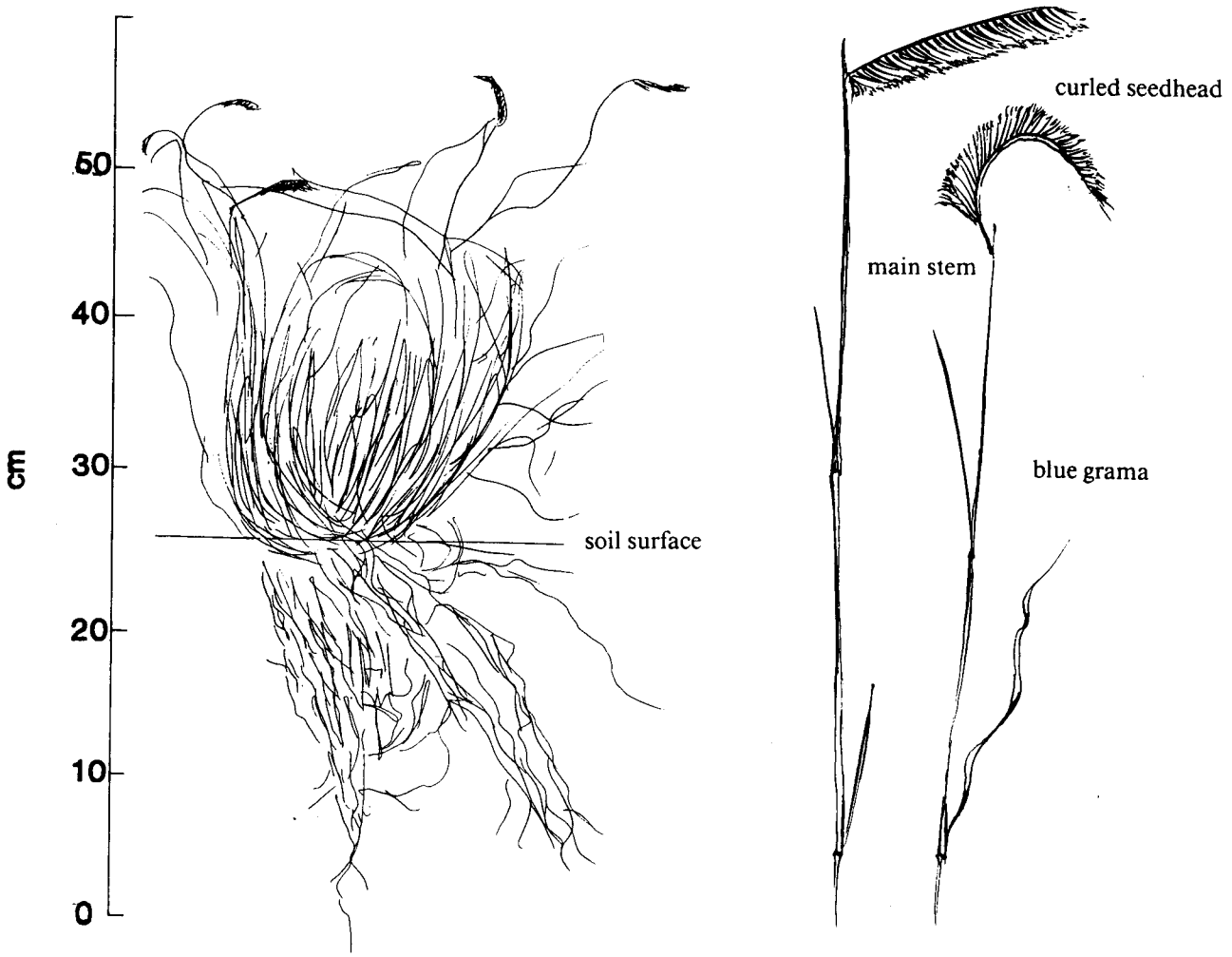
Range: Disturbed soils, gardens, roadsides.

Rooting Habit: Taproot. The main root was an elongated cone about 30 cm deep; laterals, also about 30 cm long, emerged from caudex. All roots less than 1 cm diameter.

Literature: No values found.

ROOT MEASUREMENTS OF GOOSEFOOT

Shoot Height (cm)	Crown Diameter (cm)	Caudex Diameter (cm)	Root Length Taproot (cm)
110	80	2.3	30



Blue Grama (*Bouteloua gracilis*)

Location: Two specimens of blue grama grass were excavated at Mortandad Canyon.

Soils: Alluvial sandy loam.

Habit: Perennial grass.

Plant Morphology: Perennial grass often with rhizomes growing to 60 cm. Leaf blades flat, 1-2 mm wide, 3-15 cm long. Flower heads brush-like.

Range: Dominant grass of the piñon-juniper woodland.

Rooting Habit: Roots are fibrous with greatest density within 30 cm of base.

Literature: Average rooting depth of 29 specimens 119 cm; the range was 38-396 cm.

ROOT MEASUREMENTS OF BLUE GRAMA[a]

Specimen No.	Vertical Shoot Height (cm)	Measured Lateral Root Length (cm)	Measured Root Length (cm)
1	43	73	53
2	41	72	38

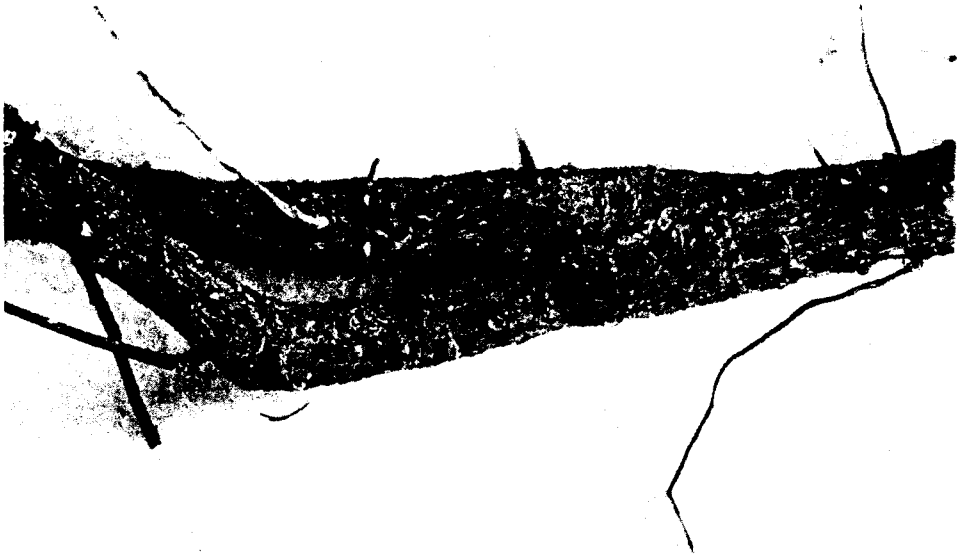
[a]These specimens were retrieved in their entirety, so measured root length is nearly maximum root length.

Appendix B. Gross Morphology

Ponderosa pine
(*Pinus ponderosa*)

Piñon pine
(*Pinus edulis*)

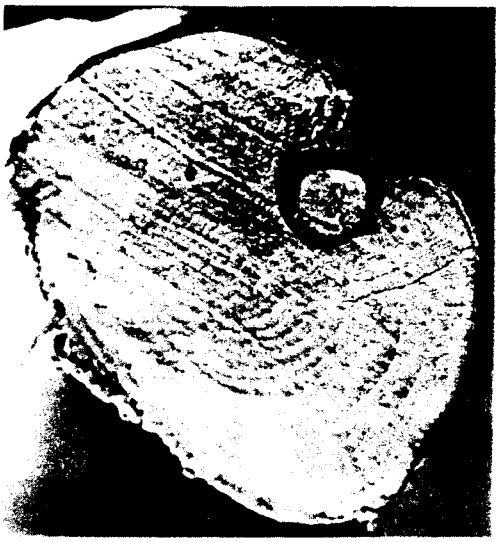
One-seed juniper
(*Juniperus monosperma*)



Quercus spp.

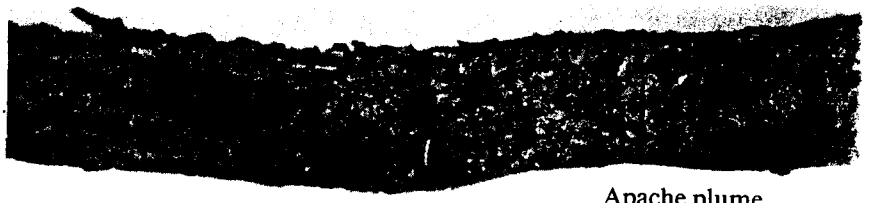
Wavyleaf oak
(*Quercus undulata*)

Gambel oak
(*Quercus gambelii*)



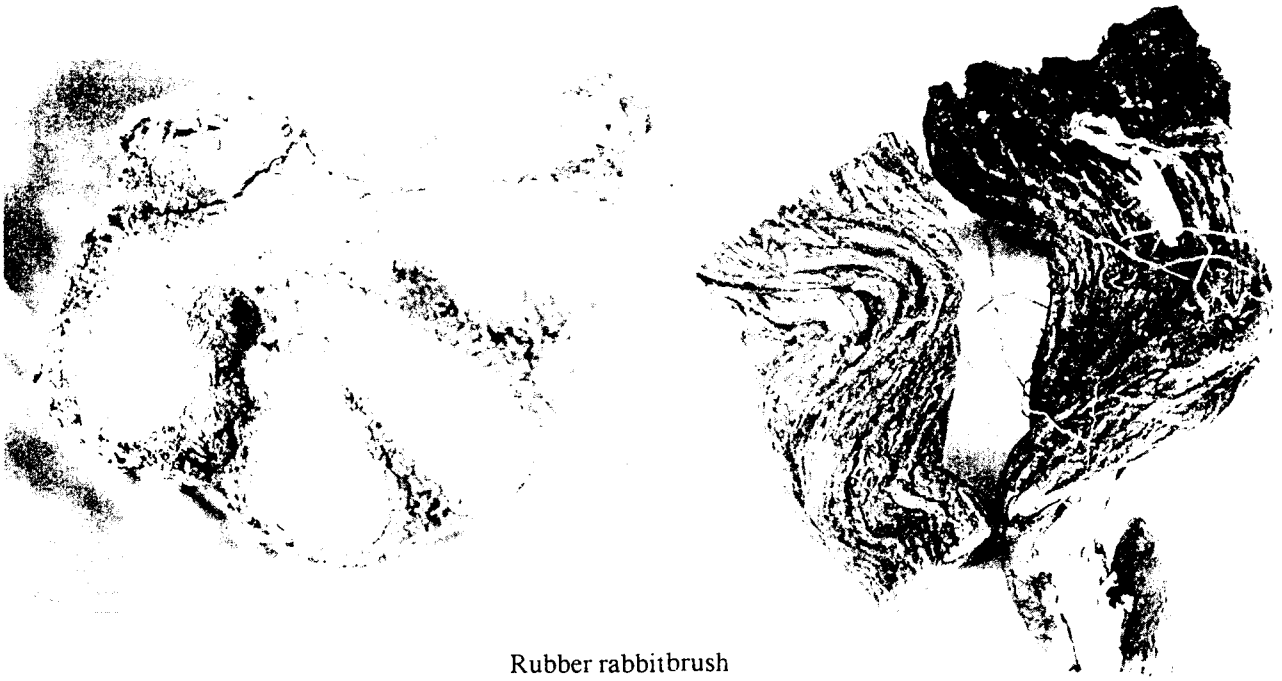
Wax currant
(*Ribes cereum*)

Wax currant
(*Ribes cereum*)



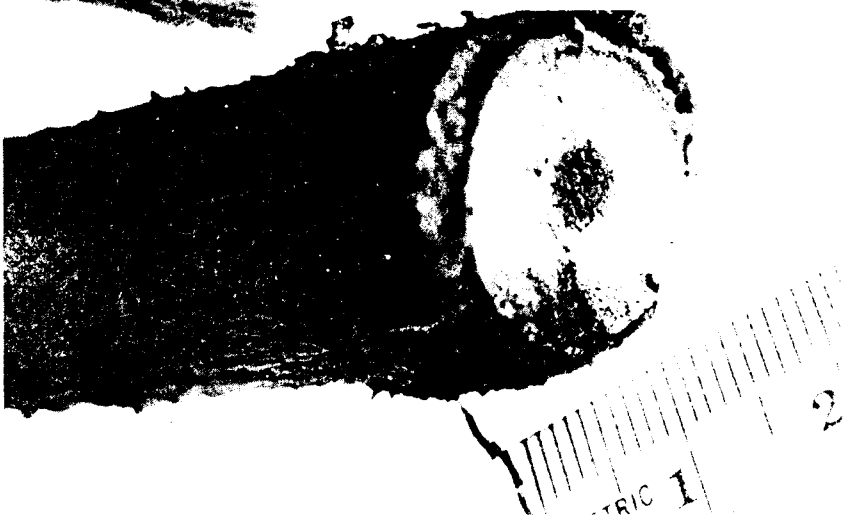
Apache plume
(*Fallugia paradoxa*)

Narrowleaf yucca
(*Yucca angustissima*)



Rubber rabbitbrush
(*Chrysothamnus nauseosus*)

Squawberry
(*Rhus trilobata*)

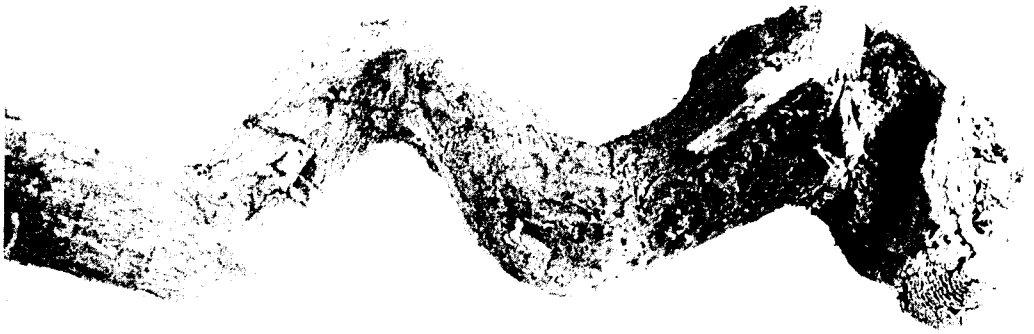


New Mexico Locust
(*Robinia neomexicana*)

Mountain mahogany
(*Cercocarpus montanus*)

Big sagebrush
(*Artemisia tridentata*)

Four wing saltbush
(*Atriplex canescans*)



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