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MASTER

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ROOTING PATTERNS IN THE PINYON-JUNIPER WOODLAND*

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ABSTRACT

An extensive bibliographical study documenting rooting patterns of native and introduced plants of the Western United States resulted in a computerized data base of over 1000 different rooting depth citations. From that data base, average rooting depths and frequencies were determined as related to species, habit, soil type, geographic region, root type, family, root depth to shoot height ratios, and root depth to root lateral ratios. Annual grasses were found to root within 1 m of the soil surface. Median rooting depth of other life forms was 2.0 m with a maximum rooting depth of 61 m. The various life forms had the following median and maximum rooting depths: annual forbs (median of 0.6 m, maximum of 3.0 m), biennial forms (0.8 m, 1.5 m), perennial grasses (1.1 m, 8.2 m), perennial forbs (1.1 m, 39.0 m), subshrubs and vines (1.2 m, 6.4 m), shrubs (2 m, 17.0 m), and trees (1.6 m, 61 m). In addition to the bibliographic study, 21 species common to the pinyon-juniper woodland were excavated from soils derived from volcanic tuff in Northern New Mexico. Rooting patterns and gross morphology were examined. Perennial forbs and grasses occurred within the first 30 cm of the soil surface. Roots of the overstory trees were traced to depths of 6 m and roots of shrubs to depths of 1.8 to 2.6 m.

INTRODUCTION

At Los Alamos National Laboratory, our primary interest in rooting depths of plants stems from regulations regarding low-level nuclear waste disposal (Nuclear Regulatory Commission 1982; Environmental Protection Agency 1983).

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The current method for disposing of low-level radioactive waste is shallow land burial. Burial trenches range in depth from 5-6 meters. These trenches are usually filled within 1 m of the surface with waste, backfilled, and capped with up to 70-90 cm of soil and 10-30 cm of topsoil.

Nuclear Regulatory Commission (1982) and Environmental Protection Agency (1983) standards for design and remedial action of disposal sites and/or mill tailings require designs to prevent intrusion or disruption for 100 years or more. Substantial earth cover could be penetrated by roots of native and introduced plants. In fact, investigations into the control and isolation of buried wastes and mill tailings have shown that deep-rooted plants may provide a pathway for the release of buried toxic materials into the biosphere (Dahlman et al. 1976, Whicker 1976, Dreesen and Marple 1980, Hakonson et al. 1981, Romney and Davis 1972, Sharitz et al. 1975). Studies at Los Alamos National Laboratory have been conducted to determine how engineering of the trench cap and placement of biobarriers can prevent intrusion (Hakonson et al. 1982).

In addition to the problem of intrusion and possible transport of hazardous materials to the surface, plant roots are important to prevention of seepage or percolation below the trench cover. Plants, through transpiration, have an effect on the water balance within the rooting zone. If evapotranspiration is maximized, seepage into the water table can be prevented eliminating a major source of transport of hazardous materials into the ecosystem. Presently at Los Alamos, studies are being conducted to determine the biological and environmental factors influencing these rates (Rodgers et al. 1984). To determine long-term changes, models such as BIOTRAN and CREAMS (Gallegos et al. 1983, Knisel 1980) are being used to predict plant-soil interactions and water-balance. Studies on rooting depths and rooting patterns are important to modeling contaminant transport through time.

To determine the best trench cap design through model simulation and basic research, two considerations are important: the prevention of intrusion of roots through the trench cap and the manipulation of the water balance within the overburden to prevent seepage and percolation. With these two criteria in mind, studies were done to determine the maximum rooting depth and the rooting ecology of plants known to invade low-level waste sites at Los Alamos National Laboratory. The intention was to develop and verify model simulations for various climatic regimes and native plant combinations for reclamation within the pinyon-juniper woodland where most of the waste sites are situated at Los Alamos.

In the rooting depth study, we were most interested in the potential for plants to disrupt a trench cap, how deeply different species root, and the likelihood of plants penetrating depths greater than 1 m where they would come into contact with waste material. This study was not meant to be physiological but instead descriptive and, when possible, quantitative. The field study, by necessity, was descriptive because excavation of roots is time consuming and laborious, making removal of enough plants for statistical analysis difficult.

DESCRIPTION OF THE STUDY AREA

Los Alamos National Laboratory is located on a plateau forming a table-like extension at the base of the Jemez Mountains in northcentral New Mexico. The Jemez Mountains are volcanic in origin, with soils derived from basalt and tuff. Climate is semiarid continental with cold winters and moderately warm summers. Elevational gradient for the study area ranges from 1642 m at the Rio Grande to 3344 m at the top of the highest peak in the Jemez range. Six different plant communities have been identified and reported (Foxx and Tierney 1980, 1984c, 1985). These include juniper grassland, pinyon-juniper woodland, ponderosa pine, mixed conifer, spruce-fir forests, and subalpine meadows. The pinyon-juniper woodland falls into two minor elevation units--one from approximately 1642 m to 1915 m on the upper edge of the Pajarito Plateau escarpment, and the other from 1915 m up to the ecotone with the ponderosa pine forest, which varies with exposure and slope from 2128 m to 2219 m. Barnes (1983) defined three habitat types within the woodlands: (1) *Juniperus monosperma/Bouteloua curtipendula* habitat type (one-seed juniper/side-oats grama), (2) *Pinus edulis, Juniperus monosperma/Bouteloua gracilis* habitat type (pinyon, one-seed juniper, blue grama), and (3) *Pinus edulis, Juniperus monosperma/Muhlenbergia montana* habitat type (pinyon, one-seed juniper/mountain mulhy).

METHODS

In 1981-1982, an extensive bibliographic study was undertaken to reference rooting depths of native and crop plants that occur within the United States. Most references were limited to studies done within states west of the Mississippi. Presently, the data base resulting from this literature search contains over 1000 different rooting citations (Foxx and Tierney 1984a,b).

Each paper referenced in the data base was examined for rooting depth information from field studies. Also included were observations, water-table depth information, and some tracer studies. Artificial plantings and lysimeter studies were excluded because of uncertainties in the comparability of the experimental and field data. Data base fields were defined as: family, species, common name, root depth, root lateral extension, root type, shoot height, life form, substrate, and geographic location and reference (Foxx and Tierney 1984b).

Once the computerized data base was created, it was searched for parameters such as rooting depth as related to life form, substrate, geographic location, and specific species. Cumulative percentage rooting frequencies were calculated when there were eight or more citations.

The field study involved excavation of species known to grow and invade low-level waste disposal sites at Los Alamos (Tierney and Foxx 1982). Twenty-one species were excavated (3 trees, 9 shrubs, 5 perennial forbs, 1 biennial forb, 2 annual forbs, 1 perennial grass) (Tierney and Foxx, In press 1985). A backhoe was used to dig a trench about 1.5 m wide and 3 m long in several locations. Excavations were seldom more than 3 m deep because of possibility of cave-ins in the alluvial soils. The remainder of the excavation of plant roots was done with hand tools. Care was taken to excavate the stoutest roots to the longest extent possible. Sometimes the entire length of the root was excavated intact but more often the root was broken at the bottom of the trench. For that reason formulae were developed to predict possible lengths (Tierney and Foxx 1982).

After the largest roots had been uncovered or delineated, the entire plant was photographed, and the rough dimensions of its root system measured to the nearest 5 cm.

DATA ANALYSIS

For this presentation, rooting depths of plants as related to life form (tree, shrub, forb, grass) were examined from the data base, disregarding the influence of substrate, geographic location, or root type. These other analyses can be found in Foxx and Tiernay 1984a and b. Information was collated for the plants that are known to occur in the pinyon-juniper woodlands of Northern New Mexico. Finally, this information was compared to field excavation data.

Depths as Related to Life Form

General observations by researchers, such as Weaver (1915, 1919, 1926, 1958), Meinzer (1927), Cannon (1911) and Cannon (1960) indicate that roots of herbaceous perennials, trees, and shrubs can penetrate to great depths if water is available. They have also observed that annuals root to the limit of the depth of seasonal rain penetration.

The computerized data base contained information for 40 evergreen trees, 107 deciduous trees, 87 shrubs, 370 perennial forbs, 36 subshrubs, 305 perennial grasses, 8 annual grasses, 9 biennial forbs, 81 annual forbs, and 4 vines. Average rooting depths and ranges of rooting depths for each of the life forms are found in Table 1. The average rooting depths for all plants recorded in the data base was 190 cm with a range of 2 to 6096 cm.

In addition cumulative percent frequency for the 1012 plants was calculated (Figure 1). Seventy-five percent of all plants rooted within 183 cm and 40% within the first meter. The median rooting depths are 12[illegible] cm. Only 6% of all specimens studied rooted deeper than 457 cm.

The cumulative rooting depth frequencies of the nine life forms for the five selected depths of 91, 183, 274, 366, and 456 cm (Table 2). The shallowest rooting life form was an annual grass. All other life forms rooted deeper than 91 cm. On a percent basis, shrubs root the deepest, followed by deciduous and evergreen trees.

Rooting Depth of Plants of the Pinyon-Juniper Woodland

The data base was then searched for information on individual plant species known to inhabit the pinyon-juniper woodlands of New Mexico (Foxx and Tierney 1985, Barnes 1983, Martin and Hutchins 1981) (Table 3). Again, geographic regions, root types, and substrate were ignored in the search parameters. Cumulative frequency (%) of rooting depths of 10 forbs and 9 grass species was calculated (Tables 4, 5). Three forb species have roots at depths greater than 457 cm, gayfeather, goldenweed, and alfalfa. Alfalfa has been reported to depths of 39 m in the roof of a mine tunnel in Nevada (Meinzer 1927) Other researchers (cited in Meinzer 1927) have reported roots of older plants to depths of over 19 m. In deep prairie soils, alfalfa has been reported to root deeper than 6 m (Weaver 1926).

Three of the 12 grasses found in woodlands and recorded in the data base had rooting depths of greater than 457 cm. They included blue grama, dropseed, and side-oats grama. Alkali sacaton (<u>Sporobolus arioides</u>) has been reported

Table 1.--Average root depth for ten life forms

Life Form	Data Base	Average (cm)	Sigma (cm)	Range (cm)
Evergreen trees	40	336	954	10-6096
Deciduous trees	107	332	451	73-3000
"All" trees	147	334	611	10-6096
Shrub	87	350	350	15-1737
"All plants	1012	190	330	2-6096
Perennial forbs	370	170	250	2-3932
"All" perennials	675	160	200	2-3932
Subshrubs	36	140	100	51- 640
Perennial grasses	305	140	90	5- 823
Annual grasses (native)	8	52	41	5- 110
Biennial forbs	9	107	38	53- 152
Annual forbs	81	80	80	4- 300
Vines	4	168	78	102- 280

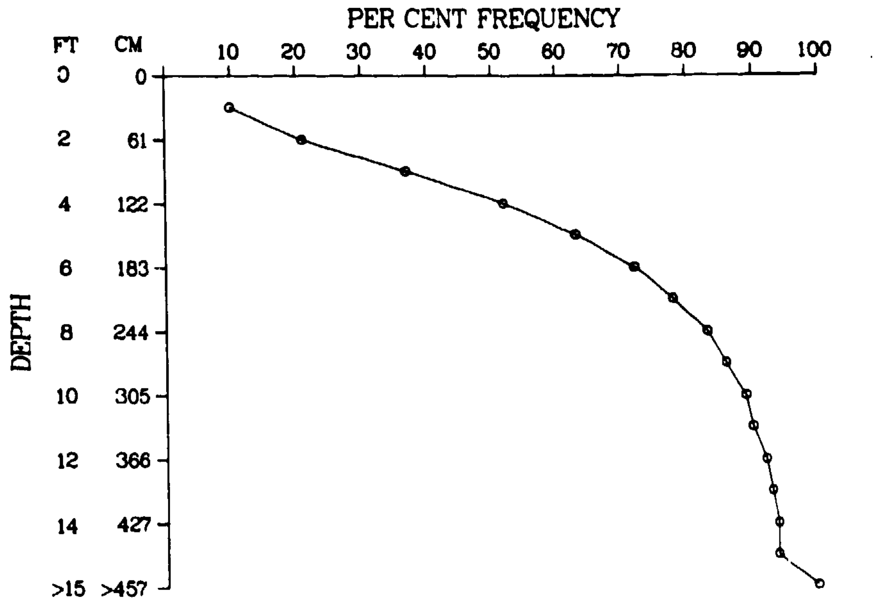

Figure 1.--Cumulative percentage frequency of rooting depth for 1012 vascular plants.

Table 2.--Cumulative rooting depth frequencies (%) for nine life forms at selected depths

Life Form	91 cm	183 cm	274 cm	366 cm	457 cm
Annual grasses	75	--	--	--	--
Biennial forbs	65	100	--	--	--
Annual forbs	65	88	97	100	--
Perennial forbs	42	71	85	93	97
Subshrubs	41	85	96	96	96
Perennial grasses	40	79	94	99	99
Evergreen trees	33	80	86	86	86
Deciduous trees	7	52	70	78	80
Shrubs	10	47	60	72	77

to root to depths of 823 cm based on water table data (Meinzer 1927). Tomanek and Albertson (1957) excavated roots of blue grama and side-oats grama to depths of 400 cm. Three-awn and downy chess were the deepest rooting annual grass species.

Field Studies

The information from the data base was compared to field studies (Tierney and Foxx, In press). Table 6 shows a comparison of the rooting depths of 21 species excavated at Los Alamos with the literature values.

Trees.--Because of the nature of the study, only small trees were excavated (3 m). We did, however, supplement the excavation information with observations of rooting depths, in large trenches (over 6 m deep) being prepared for burial of waste. Ponderosa pine roots were observed in road cuts, along arroyos, and tree fall areas as well as data from excavations.

In alluvial soils, roots of pinyons 17.0 cm diameter breast height (DBH) were traced 130 cm in depth. Ponderosa pine 10 cm DBH, on the other hand, went to 160 cm. Field observations showed ponderosa pine roots of even very large trees to be primarily in the upper 3 m of soil. This species, however, has been reported to root to depths of 25 m (Cannon 1960). Plants growing in shallow soils had well developed lateral roots that follow cracks in tuff. At Los Alamos in excavated trenches, roots

Table 3.--Rooting depths of plants of the pinon-juniper woodland (shallowest deepest)

Species	Common Name	No. In Data Base	Avg. (cm)	Range (cm)
Graminoides				
Agrostis alba	redtop	1	--	15
Agropyron trachycaulum	slender wheatgrass	1	--	25
Koeleria cristata	Junegrass	17	58	30-76
Bromus tectorum	downy chess	2	70	30-110
Festuca spp.	fescue	19	78	5-152
Carex spp.	carex	14	89	35-183
Oryzopsis hymenoides	Indian ricegrass	2	84	45-122
Poa spp.	bluegrass	9	88	35-213
Muhlenbergia montana	mountain muhly	7	91	[illegible]0-135
Sporobolus cryptandrus	sand dropseed	4	15	91-122
Bouteloua hirsuta	hairy grama	4	103	45-137
Aristida spp.	three-awn	8	108	76-152
Stipa comata	needle-and-thread	10	110	63-168
Bouteloua gracilis	bluegrama	29	119	38-396
Agropyron smithii	western wheatgrass	17	148	68-314
Andropogon scoparius	little bluestem	10	165	71-274
Agropyron desertorum	crested wheat	1	--	183
Andropogon gerardii	big bluestem	16	196	18-135
Bromus inermis	bromegrass	3	198	169-229
Bouteloua curtipendula	side-oats grama	6	222	76-396
Forbs				
Allium cernuum	wild onion	1	--	15
Castilleja spp	Indian paintbrush	2	28	25-30
Antennaria spp.	pussytoes	--	79	36-152
Mentzelia spp.	blazing star	3	58	11-152
Achillea spp.	yarrow	5	63	14-183
Salsola kali	Russian thistle	1	--	67
Arenaria spp.	sandwort	3	77	38-117
Antennaria parvifolia	pussytoes	3	40	36-48
Vicia spp.	vetch	2	80	20-140
Amaranthus spp.	pigweed	3	9	10-240
Hymenoxys richardsonii	pinque	1	--	90
Solanum elaeagnifolium	horse-nettle	7	93	15-152
Senecio spp.	groundsel	6	94	20-154
Artemisia frigida	estafiata, wormwood	15	104	46-244
Gaillardia spp.	blanketflower	2	103	76-130
Potentilla spp.	cinquefoil	3	110	10-240
Ratibida spp.	coneflower	3	112	46-183
Yucca spp.	yucca	7	112	30-213
Grindelia spp.	gumweed	5	115	43-185
Chenopodium album	lamb's quarters	1	---	119
Cucurbita foetidissima	coyote melon	1	--	122
Penstemon spp.	beardstongue	7	129	36-305
Melilotus spp.	sweetclover	3	130	85-152
Aster spp.	aster	5	154	15-335
Eriogonum spp.	buckwheat	9	165	64-305
Petalostemum spp.	prairie clover	4	166	85-213
Geranium spp.	geranium	2	180	86-274
Lupinus spp.	lupine	4	182	168-240
Artemisia dracunculus	false terragon	1	--	213
Kochia scoparia	summer cypress	1	--	200
Oenothera spp.	evening primrose	5	209	53-305
Lithospermum spp.	puccoon	6	220	183-305
Sphaeralcea spp.	globe mallow	5	262	80-396
Gaura spp.	gaura	7	252	76-427
Soladago spp.	goldenrod	9	255	107-335
Chrysopsis villosa	goldenaster	5	275	130-396
Haplopappus spp.	goldenweed	6	287	107-518
Liatris punctata	gayfeather	6	308	120-479

Table 3 (cont)

Species	Common Name	No. In Data Base	Avg. (cm)	Range (cm)
Glycyrriza spp.	wild licorice	3	395	360-428
Medicago sativa	alfalfa	13	690	38-3900
Subshrub				
Gutierrezia spp.	snakeweed	10	122	51-244
Shrubs				
Fallugia paradoxa	Apache plume	2	115	60-140
Cercocarpus montanus	mountain mahogany	4	113	40-152
Quercus gambelii	Gambel's oak	2	238	80-396
Artemisia tridentata	big sagebrush	9	248	110-914
Chrysothamnus nauseosus	chamisa (rabbitbrush)	5	293	100-457
Rosa spp.	wild rose	5	391	91-640
Atriplex canescens	four-wing saltbush	3	392	110-762
Trees				
Ulmus pumila	elm	1	127	127
Pinus ponderosa	ponderosa pine	1	447	10-2438
Pinus edulis	pinon pine	1	---	640
Juniperus monosperma	one-seed juniper	3	2438	579-6096

Table 4.--Cumulative frequency (%) of rooting depths of forbs

Forb	Root Depth					
	91	183	274	366	457	>457
Yucca	57	71	100	--	--	--
Cinquefoil	57	85	100	--	--	--
Wormwood	53	92	100	--	--	--
Buckwheat	22	66	88	100	--	--
Goldenrod	0	30	40	100	--	--
Beardstongue	57	86	86	100	--	--
Puccoon	0	34	67	100	--	--
Alfalfa	17	41	57	57	57	100
Goldenweed	0	50	67	84	84	100
Gayfeather	0	17	50	65	83	100

Table 5.--Cumulative frequency (%) of rooting depths of grasses

Grass	Root Depth				
	91	183	274	366	457
Junegrass	100	--	--	--	--
Bluegrass	72	100	--	--	--
Fescue	64	100	--	--	--
Three-awn	50	100	--	--	--
Needle-and-thread	40	100	--	--	--
Mountain muhly	15	58	100	--	--
Wheatgrass	19	77	95	100	--
Dropseed	37	75	75	85	100
Side oats grama	17	50	67	83	100

Table 6.--Comparison of Rooting Depths of Species with Literature values found by Foxx et al. (1984a,b)

Common Name and Scientific Name	Excavated Depths (cm)	Literature Values Average (cm)	Literature Values Range (cm)
pinyon pine *Pinus edulis*	110,130,640	---	---
ponderosa pine, *Pinus ponderosa*	160,150	447	10-2438
one-seed juniper, *Juniperus monosperma*	170,640	2438	579-6096
chamisa, *Chrysothamnus nauseosus*	140,180,210	147	100-457
Squawberry, *Rhus trilobata*	210,230	---	---
Apache plume, *Fallugia paradoxa*	170,290,260	---	---
mountain mahogany, *Cercocarpus montanus*	50	113	40-152
wax currant, *Ribes cereum*	80,290	---	---
New Mexico locust, *Robinia neomexicana*	140,100	---	---
Oak, *Quercus* spp.	150,175,320	238	80-396
four-wing saltbush, *Atriplex canescens*	185,220	314	80-762
big sagebrush, *Artemisia tridentata*	130,130	248	110-914
snakeweed, *Gutierrezia sarothrae*	24,34,32	122	51-244
narrowleaf yucca, *Yucca angustissima*	20,20	113	40-152
prickly pear, *Opuntia polyacantha*	8,10,28	77	2-366
lupine, *Lupinus caudatus*	200	182	168-240
pinque, *Hymenoxys richardsonii*	23,25	---	90
mullein, *Verbascum thapsus*	28,42	---	---
lamb's quarters, *Chenopodium fremontii*	30	---	---
sunflower, *Helianthus petiolaris*	45	---	69
Blue grama, *Bouteloua gracilis*	53,58	119	38-396

of pinyon and juniper were traced in cracks in the tuff to depths of 6.4 m. The literature values indicated most trees to root to between 91-123 cm from the surface. Deciduous trees root somewhat deeper than evergreens.

Shrubs.--Four distinct rooting patterns were observed in the nine shrubs excavated. Apache plume and chamisa (Fig. 2a) had well developed taproots that descended directly downward to depths of 2 or more meters. The oaks and New Mexico locust had rather distinct taproots with laterals forming sprouts. (Fig. 2b). Four-wing saltbush and sagebrush had numerous small roots in the upper soil surface with larger lateral roots descending from the caudex (Fig. 2c). Squawbush, mountain mahogany, and currant had large stem clump bases from which rather stout lateral roots emerged (Fig. 2d). In alluvial soils these descended downward to depths of 100-320 cm. In shallow soils underlain by tuff, the roots penetrated to the depth of the bedrock, then grew at right angles until encountering a crack, and then descended downward.

The data base contained information on 87 different shrub specimens with an average rooting depth of 350 cm. The medium rooting depth was 195 cm, but over 20% of the specimens recorded rooted to depths greater than 457 cm. Woodbury (in Meinzer 1927) reported roots of big sagebrush to depths of over 9 m. We found sagebrush to root to approximately 2 m in alluvial soils and most other species to less than 3 m.

Forbs.--At Los Alamos five perennial forbs were excavated and roots traced: pinque, estafiata, snakeweed, yucca, and lupine. Although yucca is rhizomatous, it was included in the studies because it often invades disturbed areas in the pinyon-juniper woodland. Whole plants of pinque, estafiata, and snakeweed were excavated and were found to root to depths of 25 cm. Lupine, however, rooted to depths of greater than 2 m. The root of the lupine was a distinct tap root that descended rapidly, whereas the roots of the other two perennial species were a single taproot with a number of laterals. The yucca was found to root to 30 cm. Numerous sprouts formed other plants from the rhizome.

Perennial forbs comprised the largest number of entries in the data base (370). Average rooting depths were 170 cm with a range from 2 to 3920 cm. Again, the greatest depths were reported for plants with roots penetrating mine tunnels. The common alfalfa (*Medicago sativa*) is one of the deepest rooting perennial forbs. At Los Alamos, the deepest rooting perennial forb excavated was lupine. Interestingly, rooting depths of three families were compared in the data base, legumes (*Fabaceae*) rooted the deepest, then composites (*Asteraceae*), and grasses (*Poaceae*) the shallowest (Foxx and Tierney 1984a). Legumes are often used for reclamation or invade disturbed ground.

The highest frequency of rooting depths for perennial forbs was 92 cm. Median rooting depth of 114 cm was found. Only 4% of all occurrences rooted deeper than 457 cm.

Biennial forbs.--At Los Alamos we excavated only one biennial species, mullein. This weedy plant can grow to a height of 7 feet. Our specimens were approximately 3 feet tall and rooted to depths of 40 cm in alluvial soils. This root depth was below the average and median rooting depths for the nine biennial forbs in the computerized data base. The average rooting depth for those nine plants was 107 cm with a range of 53 to 152 cm. The common sweet clover was the most deeply rooted biennial genus. The highest rooting frequencies occur from 91 to 152 cm. Median rooting depth is 76 cm. No specimens rooted deeper than 152 cm.

Annual forbs.--Two annual forbs, lamb's quarters and sunflower, were excavated. The roots of these species were traced to depths of 45 and 30 cm, respectively. At 30 cm, the roots of the lamb's quarters turned at a right angle and may have gone much deeper. The average rooting depth for the 81 annual forbs recorded in the computerized data base was 80 cm, with a median rooting depth of 61 cm. The highest rooting frequency was 123 cm. There were no annual forbs that rooted deeper than 305 cm recorded in the data base.

Grasses.--The most common perennial grass of the pinyon-juniper woodland in northern New Mexico is blue grama. It was excavated in alluvial soils and roots were measured to 58 cm. No annual grasses were excavated.

On an average, the perennial grasses recorded in the data base were found to root to a depth of 140 cm with a range of 5 to 823 cm, whereas the average rooting depth of annual grasses was 52 cm.

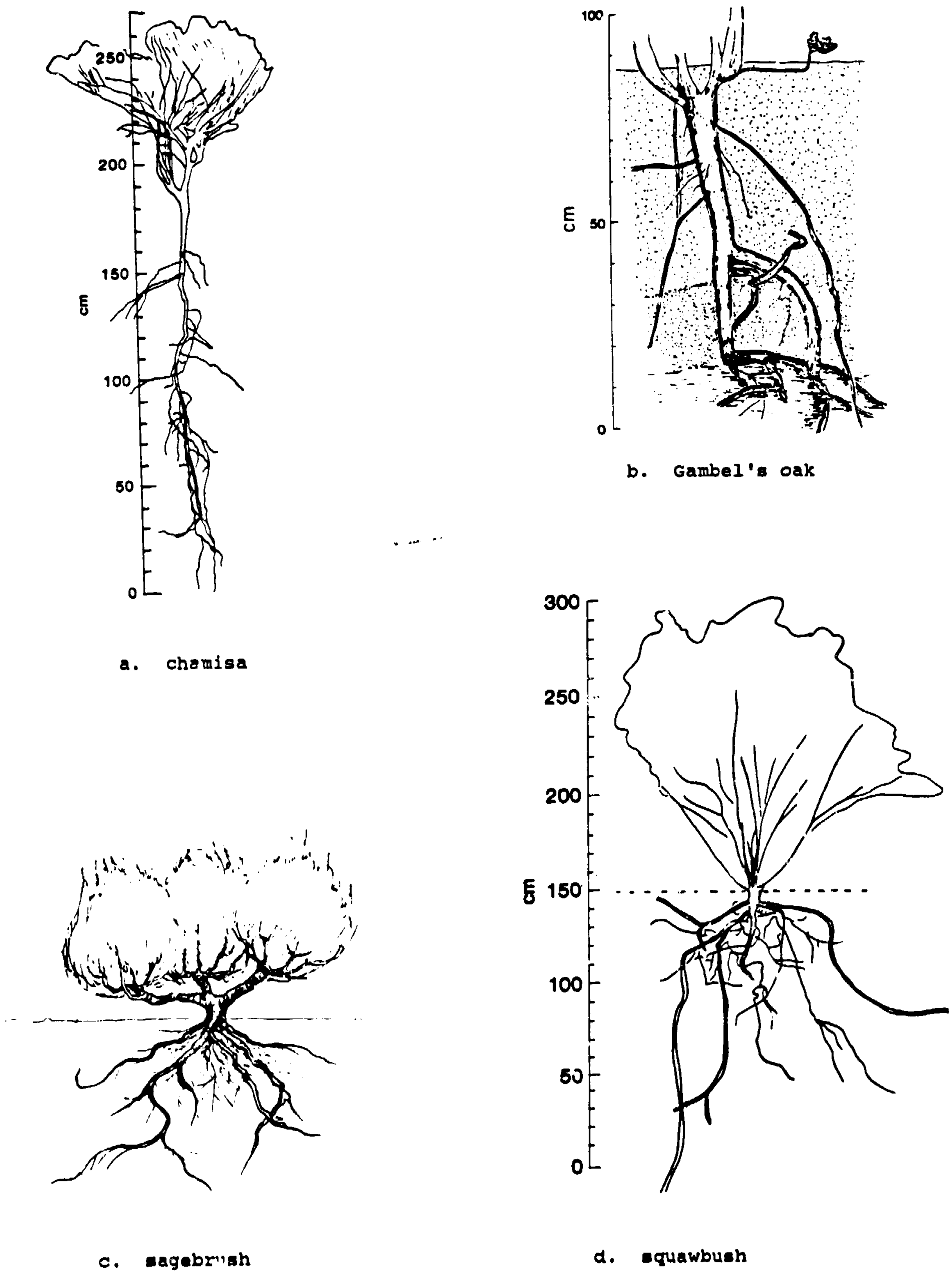

Figure 2.--Rooting patterns of shrubs in the pinyon-juniper woodland.

CONCLUSIONS

Examination of the computerized data base of rooting depths of species found in various soils in the states west of the Mississippi showed that the annual grass roots were found entirely within 1 m of the soils surface. Median rooting depths of other life forms were 2.0 m, with maximum rooting depths of 61 m. The other life forms had the following median and maximum rooting depths: annual forbs (median of 0.6 m, maximum of 3.0 m); biennial forbs (0.8 m, 1.5 m); perennial grasses (1.1 m, 8.2 m): perennial forbs (1.1 m, 39 m); subshrubs and vines (1.2 m, 6.4 m): trees (1.6 m, 1.5 m); shrubs (2 m, 17 m).

Field excavations of 21 species found within the pinyon-juniper woodland showed that roots of pinyon pine and one-seed juniper could extend to depths of 6 m in fractures in tuff. Roots of shrubs were the most varied, some with distinct deeply rooting taproots and others with more extensive root systems to the surface. In all cases, even in alluvial soils the rooting depths of species found in these volcanic soils were somewhat shallower than those means found from the collated literature values.

This study emphasizes the importance of the engineering of a trench cap on waste sites to accommodate the rooting patterns of planted and successional species. The data base suggests that most plants root to levels below 1 m and 90% of all the specimens examined root to depths of 2 m. Because the present overburdens are generally only 1 m deep, penetration of roots into the waste zone is certain if biobarriers are not employed. In trench cap design, the data base can be predictive in suggesting which plants may be appropriate to reclamation of sites where rooting depths are important. In addition, the data base can be useful in determining the possible rooting patterns of successional species in various plant communities, including the pinyon-juniper woodlands found throughout the western United States and eliminate time intensive excavations. The study provided some basic information needed for model development and simulation.

Information on the physiology of roots at various depths is important to an understanding of the influence of plants to the water balance and contaminant transport of waste sites in any plant community. Such information was not within the scope of this study and needs further investigation.

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