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Rooting Depths of Plants Relative to Biological and Environmental Factors

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This work was supported by the US Department of Energy, Office of Defense Waste and Byproduct Management.

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ROOTING DEPTHS OF PLANTS RELATIVE TO BIOLOGICAL AND ENVIRONMENTAL FACTORS

by

Teralene S. Foxx, Gail D. Tierney, and Joel M. Williams

ABSTRACT

In 1981-1982 an extensive bibliographic study was completed to document rooting depths of native plants in the United States. The data base presently contains 1034 citations with approximately 12 000 data elements. In this paper the data were analyzed for rooting depths as related to life form, soil type, geographical region, root type, family, root depth to shoot height ratios, and root depth to root lateral ratios. Average rooting depth and rooting frequencies were determined and related to present low-level waste site maintenance.

I. INTRODUCTION

In recent years, the extent to which vascular plants perturb or stabilize shallow land burial (SLB) sites or mill tailing sites has become of interest. To meet proposed Environmental Protection Agency (Federal Register 1981, performance standards on low-level waste (LLW) sites, site personnel must make an effort to reduce infiltration of water through the trench cover and intrusion of roots into waste. Management of such sites requires recognition of the complex interaction between physical, chemical, and biological processes occurring at the site.

Plant cover and hydrological interactions, however, are highly variable through time; all possible changes cannot be measured in the field. Therefore, mathematical models such as CREAMS (Chemical, Runoff, and Erosion from Agricultural Management Systems) hold promise in the prediction of chemical transport, runoff, erosion, infiltration, evaporation, transpiration, and soil moisture in trench covers under a variety of conditions (Knisel 1980). In addition, models such as BIOTRAN (Biological Transport) can be used to predict growth and uptake of radionuclides by plants and also transport through the food chain (Gallegos et al. 1983, Gallegos et al. 1980). Some parameters, including rooting ecology of native species, have not yet been fully defined for either model. For this reason, an extensive literature review of rooting depths and rooting ecology of vascular plants with emphasis on native plants was done. This information was entered into a data base to obtain information on rooting depths as related to family, species, life form, soils, root type, and geographical and climatic region.

A. Plants and Trench Cover Design

In the designing of trench covers for LLW sites, plants are important for two reasons:

- the need to prevent intrusion of roots through the overburden, and
- the need to prevent seepage or percolation below the trench cover, and surface runoff.

1. Root Intrusion. Ideally, the trench cover design should preclude the possible uptake of contaminants by plants by optimizing the type and depth of soil and the plant species (or community) used in revegetation. It has been established that plants can be involved in radionuclide uptake (Hakonson et al. 1981, Romney and Davis 1972, Sharitz et al. 1975, Biddolph et al. 1960) and therefore provide a pathway for radionuclides to migrate into biological pathways. It has also been demonstrated that radionuclide uptake by vegetation occurs on LLW sites at Savannah River, Maxey Flats, West Valley, Oak Ridge, Los Alamos, and Hanford (USDOE 1980, Jacobs et al. 1980, Clancy et al. 1981, Hakonson and Bostick 1976). Excavation studies at Los Alamos National Laboratory have demonstrated plant roots in contact with waste in a decommissioned LLW site.

The need for information on rooting ecology of vegetation used in stabilizing waste disposal facilities is twofold:

- to select optimum species for controlling root intrusion and water-related problems, and
- to account for changes in species composition on waste sites due to natural succession.

Studies on trench cap design for prevention of root intrusion (Hakonson and White et al. 1982, Cline et al. 1980) have been for the most part limited to rapidly growing species rather than deep-rooted perennials, trees, or shrubs. These life forms most often invade well-established waste sites (Tierney and Foxx 1982). Knowledge about rooting ecology as influenced by biological or engineering design is essential.

2. Seepage, Percolation, Runoff, and Vegetation. Problems of trench cap integrity are directly related to seepage, percolation, and runoff. It is by these hydrologic processes that contaminants are transported from the

burial site to ground water or soil surfaces outside the site. Plant cover and the soil profile determine the distribution of precipitation, amounts of surface runoff, infiltration of water into the soil profile, as well as the amounts of water leaving the soil profile through evaporation, transpiration, or percolation. Water penetrating below the rooting zones of the plants is most likely to penetrate into wastes. The amount of seepage below this zone is directly affected by the soil profile, soil moisture, water-holding capacity of the soil, plant root depth, and evapotranspiration. Thus, knowledge about plant rooting depth and evapotranspiration rates becomes extremely important in trench cap design. Figure 1 conceptualizes these interactions (Hakonson and Lane et al. 1982).

B. Factors Which Affect the Rooting Depth of Plants

The rooting depth of a species is primarily governed by heredity, but depth is also a product of the environment in which the plant grows. Regardless of ideal environmental conditions, roots will penetrate only as deep as that plant's genetic make-up allows. Specific environmental conditions may cause this depth to vary from plant to plant within a species. Nutrients available from the aerial parts and soil, oxygen supply, soil moisture content, osmotic pressure, soil temperature, pathogens, soil pore size, and

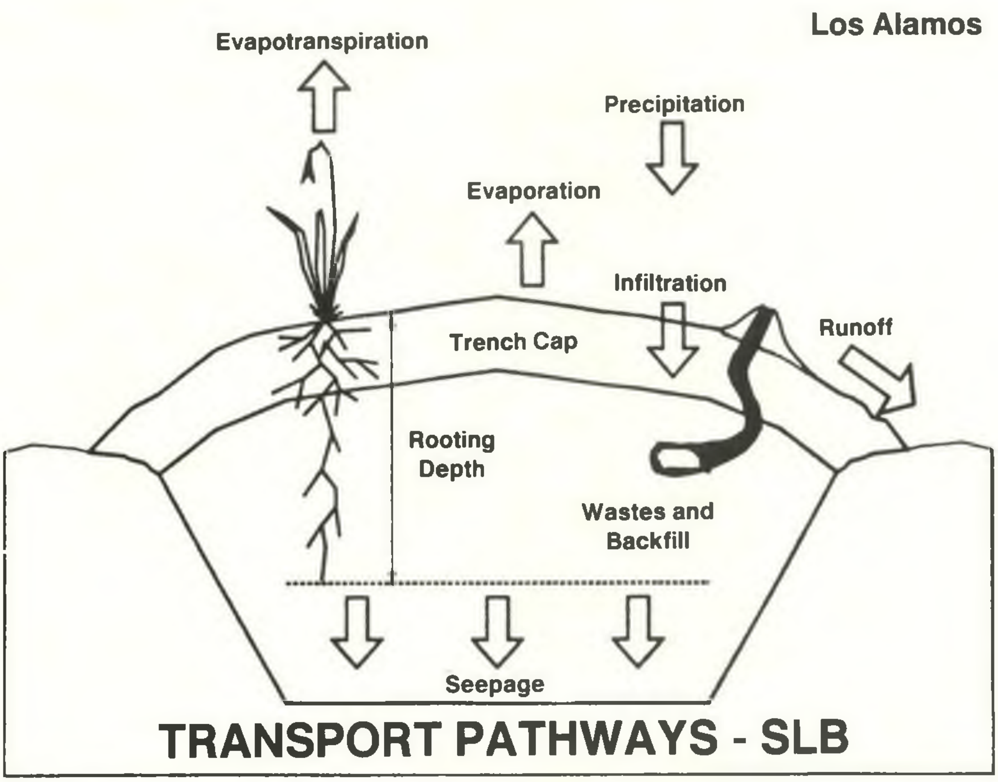

Figure 1. Water and biota--related processes contributing to radionuclide transport at shallow land burial low-level radioactive waste sites (Hakonson and Lane et al. 1982).

soil compaction may vary root penetration (Russell and Russell 1973, Weaver and Clements 1938). These specific factors are further discussed in additional papers on rooting ecology.*,**

II. METHODS

This literature review was conducted in 1981-1982 to summarize existing knowledge on the rooting depths of native and crop plants that occur within the United States. Most of the references used in this review were limited to studies done within the United States in states west of the Mississippi. The information is currently stored on Los Alamos National Laboratory's NOS computer under System 2000. The data base contains currently (June 1983) 1034 different rooting citations with approximately 12 000 data elements.

Each reference was examined for rooting depth information based upon field studies. Artificial plantings and lysimeter studies were excluded because of uncertainties in the comparability of the experimental versus field data. Included were observations, water-table depth information, and some tracer studies. Fifty-six data elements were defined; one-half were used. The major elements include

- family,
- species,
- common name,
- root depth,
- root lateral extension,
- root type,
- shoot height,
- life form,
- substrate,
- geographic location, and
- reference.

III. DATA ANALYSIS OF ROOT DEPTH RELATIONSHIPS

No known summarization of the literature concerning depth of rooting of vascular plants as related to biologic and environmental factors has been made. General observations by researchers, such as Weaver (1926, 1919, 1915a, 1915b, 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 and that rooting depth of annuals will

*Foxx, T. S., G. D. Tierney, and J. M. Williams. 1983a. Rooting depths of plants on low-level waste disposal sites. Los Alamos National Laboratory (in press).
**Foxx, T. S., G. D. Tierney, and J. M. Williams. 1983b. Rooting depth of vascular plants, A Review, Los Alamos National Laboratory (in press).

be limited to the depth of the seasonal rain penetration. Essential to the design and maintenance of biobarriers in LLW sites is a knowledge of the extent of rooting or the ability to predict the root depth and lateral extension of trees, shrubs, grasses, or forbs used to revegetate a site. This data base contains references to rooting depths of 1012 specimens, shoot heights for 94 specimens, and root lateral extensions for 248 specimens. The data base was searched for rooting depths as related to the following:

- life form,
- soil type,
- evaporative regions,
- root type,
- families - taxonomic relationships,
- root depth to shoot height ratios, and
- root depth to root lateral ratios.

A. Life Form

Average rooting depths, frequency of rooting, and extent of rooting were examined for each of the life forms: trees, shrubs, subshrubs, and perennial, annual, and biennial grasses and forbs. In addition, where possible, root depth to shoot height ratios and root depth to root lateral ratios were determined as a factor in prediction of rooting depth or rooting extensions.

1. Trees. Trees are woody species with one or more stems called trunks. They may be deciduous (losing leaves as autumn begins) or evergreens (retaining some leaves throughout the year). The data base contains rooting depths for 147 trees (40 evergreen and 107 deciduous). The average rooting depth for all trees is 334 cm with a range of 10 to 6096 cm (Table I). Six different specimens have been reported to root deeper than 1000 cm. They were apple (*Pyrus malus* L.), white pine (*Pinus sylvestris*), poplar (*Populus euramericana*), locust (*Robinia* spp.), tamarisk (*Tamarix* spp.), ponderosa pine (*Pinus ponderosa* Laws.), and one-seed juniper (*Juniperus monosperma* Engelm.) (Engelm.) Sarg. Deep extensions of roots were most often reported for mine shafts in arid or semi-arid regions (Cannon 1960) or based on water table information (Meinzer 1927).

The average rooting depth for deciduous trees was 332 cm (Table I) with a range of 73 to 3000 cm, tamarisk being the deepest rooting species. The average rooting depth for evergreen species was 336 cm, with a range of 10 to 6092 cm (Table I).

Rooting frequencies were calculated for all trees, evergreen trees, and deciduous trees (Fig. 2). Median rooting depth for evergreen trees is 116 cm; deciduous trees commonly root deeper, with a median at 189 cm. Eighty per cent of all specimens recorded as evergreen root within the 457-cm depth, while 86% of the deciduous species root within 457 cm.

TABLE I

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)	50	52	41	5- 110
Biennial forbs	9	107	38	53- 152
Annual forbs	81	80	80	4- 300
Vines	4	168	78	102- 280

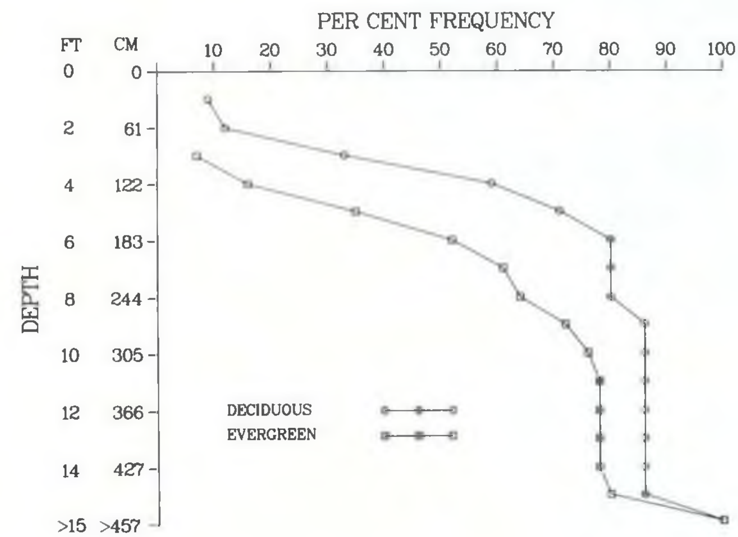

Fig. 2. Cumulative per cent frequency of rooting depth of deciduous and evergreen trees.

Root depth to shoot height ratios (d/h) were calculated for evergreen tree species recorded in the data base (Table II). The d/h ratio was 0.57. Trees (7) less than 305 cm tall had a ratio of 0.97, while trees greater than 305 cm tall had a 0.22 ratio. The tallest tree, Pinus blanksiana, (1372 cm tall) had a 0.12 ratio. The shortest tree (8 cm) had a 2.5 ratio. Sprackling and Read (1979) summarized d/h ratios for 392 deciduous trees in eastern Nebraska. The mean d/h ratio was 0.42, bur oak (Quercus melanocarpa) having the highest ratio of 0.62 and peachleaf willow (Salix amygdaloides Anderss.) having the lowest ratio of 0.23. The data base had only one shoot height entry for deciduous trees: aspen (Populus tremuloides) Michx., with a d/h ratio of 0.12.

Radial root lateral spread to shoot height (ls/h) was calculated for 17 evergreen trees (Table II). The ls/h ratio for all the evergreens was 1.2. For the eight trees less than 305 cm tall the ls/h ratio was 1.7; trees greater than 305 cm tall had a ratio of 0.87. The average lateral extension for trees less than 305 cm tall was 179 cm, while the average lateral extension for species over 305 cm was 599 cm. The tallest tree (1372 cm) had a ls/h ratio of 0.62; the shortest tree (8 cm) had a ls/h ratio of 1.0. Sprackling and Read (1979) found a mean ls/h ratio of 1.39 for 392 deciduous trees. The highest ratio was 2.09 for 32 honeylocusts and 0.87 for 14 peachleaf willows.

Root depth to radial root lateral spread (d/ls) was calculated for 18 evergreen trees (Table II). The d/ls was 0.64 for all evergreens. Ratio for the nine trees less than 305 cm was 1.03, whereas ratio for the nine trees

TABLE II

MEAN RATIOS FOR DEPTH, SHOOT HEIGHT, AND RADIAL LATERAL ROOT SPREAD

Life Form	No.	d/h*	d/ls**	ls/h***
Deciduous trees	392	0.42	0.36	1.39
Evergreen trees	17	0.57	0.64	1.2
Shrubs	15	1.2	0.85	2.5
Grasses	10	2.0	1.8	2.7
Forbs	34	1.7	--	2.0
	136	--	2.3	--
Subshrubs	12	--	4.4	--

*d/h = depth to shoot height.
**d/ls = depth to lateral spread.
***ls/h = lateral spread to shoot height.

taller than 305 cm was 0.26. The average rooting depth for trees less than 305 cm was 60 cm and average height was 101 cm. The average rooting depth for trees greater than 305 cm was 151 cm and the average height was 730 cm. The tallest (1372 cm) evergreen had a d/ls ratio of 0.20; the shortest tree (8 cm) had a ratio of 2.5. Sprackling and Read (1979) found a d/ls ratio for 392 deciduous trees was 0.36. They found the d/ls ratios changed with tree age. Mean ratios for trees 2-5 years was 0.55; 6-10 years, 0.31; 11-25 years, 0.30; 26-49 years, 0.32; and greater than 49 years, 0.26.

2. Shrubs. Shrubs are woody species with multiple stems generally growing less than 488 cm tall. The data base contained 87 different references to shrubs with an average root depth of 350 cm (Table I). Root depths ranged from 15 to 1737 cm. Deepest measurements have been reported for roots found in the roof of mine tunnels in the western United States (Meinzer 1927). The deepest rooting shrubs are buffaloberry (*Shepherdia* spp.), live oak (*Quercus agrifolia* Nee), desert willow (*Chiopsis linearis* (Cav.) Sweet), and greasewood [*Sarcobatus vermiculatus* (Hook) Torr. (Meinzer 1927)]. Woodbury reported roots of big sagebrush (*Artemisia tridentata* Nutt.) to depths of over 900 cm (Cannon 1960).

Root depth frequencies for all shrubs are given in Fig. 3. Median rooting depth is 195 cm, but over 20% of the specimens recorded rooted to depths greater than 457 cm. Of the specimens recorded, 77% rooted less than 457 cm deep.

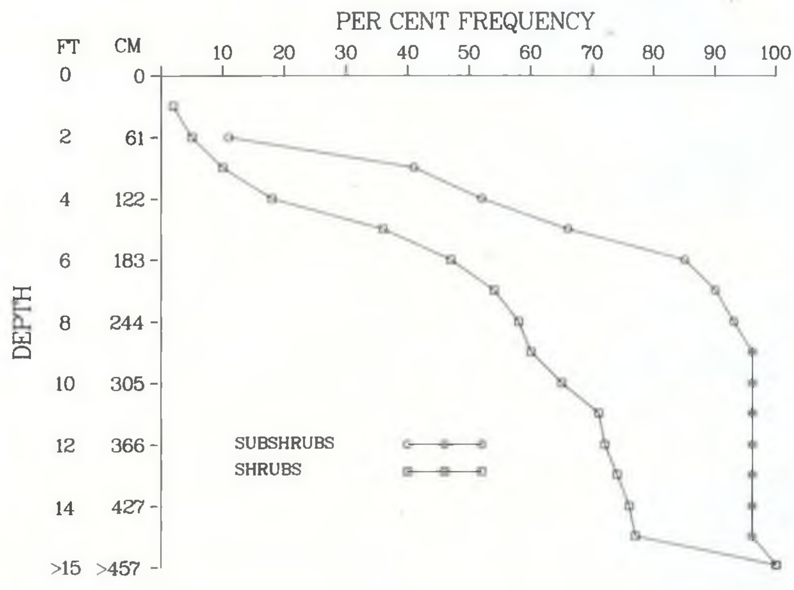

Fig. 3. Cumulative per cent frequency of rooting depth of forbs.

Mean root depth to shoot height ratios (d/h) were calculated for 15 shrubs. The d/h ratio was 1.2. The lowest ratio was 0.09 for Fouquiera splendens Engelm., and the highest ratio, 3.9 for Artemisia tridentata (Table II).

Mean radial lateral spread to height ratios (ls/h) were calculated for 15 shrubs. The mean was found to be 2.5. The highest ratio was 3.3 for Artemisia tridentata, and the lowest, 0.29 for Fouquiera splendens.

The mean root depth to radial root lateral ratio (d/ls) was 0.85. The highest ratio was for Amorpha canescans Pursh., the lowest for Rhus copallina L.

The average lateral extension for the 17 shrubs was 250 cm (Table III). The longest laterals were 1660 cm for Rhus copallina. When the extremes are removed the average lateral extension is 236 cm. Average root depth is 171 and average shoot height is 149 cm.

3. Subshrubs. Subshrubs are low-growing woody species less than 30 cm tall. There are 36 subshrubs recorded in the data base. The average rooting depth (Table I) is 140 cm with a range of 51 to 640 cm. The deepest rooting species are big-berried manzanita (Arctostophylos glauca Lindl.) in an unknown substrate and wild rose (Rosa suffulta Greene) in a silty soil.

Rooting frequencies are shown in Fig. 3. The largest numbers of specimens root at 91 cm and 183 cm. Median rooting depth is 116 cm. Only 4% of the specimens root deeper than 457 cm.

The data base contained information on root depth versus lateral spread (d/ls) of only 12 specimens (Table II). The mean d/ls ratio was found to be

TABLE III

AVERAGE ROOT LATERAL EXTENSION FOR SEVEN LIFE FORMS

Life Form	Average (cm)	Sigma (cm)
Trees	580	630
Shrubs	250	340
Annual forbs	150	190
Annual grasses	180	250
Perennial forbs	110	210
Perennial grasses	60	60
Subshrubs	26	19

4.4. The average rooting depth for the 12 specimens was 124 cm with an average lateral spread of 37 cm.

4. Perennial Forbs. Perennial forbs are nongraminoid (grass) herbaceous species living more than 2 years. The largest number of entries (370) in the data base is in the perennial forb category. Average rooting depths are 170 cm with a range from 2 to 3920 cm (Table I). Again, the greatest depths were reported for plants with roots penetrating mine tunnels. The common alfalfa (*Medicago sativa* L.) is one of the deepest rooting perennial forbs. It has been reported to depths of over 3900 cm in the roof of a mine tunnel in Nevada (Meinzer 1927). Other researchers (Meinzer 1927) have reported roots of older plants to depths of over 1900 cm. In deep prairie soils, alfalfa has been reported to root deeper than 600 cm (Weaver 1926).

Rooting frequencies are shown in Fig. 4. The highest frequency is at 92 cm for all perennial forbs recorded. Median rooting depth is 114 cm. Only 4% of all occurrences recorded rooted deeper than 457 cm.

5. Biennial Forbs. This nongraminoid life form lives for 2 years; the first year is usually confined to vegetative growth; the second, to reproduction. Only nine references were found for biennial forbs. The average rooting depth (Table I) was 107 cm with a range of 53 to 152 cm. The common sweet clover (*Melilotus* spp.) was the most deeply rooting biennial genus.

Rooting frequencies are shown for this group in Fig. 4. The highest rooting frequencies occur from 91 cm to 152 cm. Median rooting depth is 76 cm. No specimens rooted deeper than 152 cm.

6. Annual Forbs. Annual forbs are nongraminoid (grass) species, which complete the life cycle in 1 year. A total of 81 different rooting depths were recorded. The average rooting depth (Table II) is 80 cm with a range of 4 to 300 cm.

Rooting depth frequencies are shown in Fig. 4. The highest rooting frequency for all specimens was at 123 cm. Median rooting depth is 61 cm. No specimens root deeper than 305 cm.

Mean root depth to shoot height ratios (d/h) were calculated for 34 forb specimens. The d/h ratio was 1.7 (Table II). Fifty per cent of the specimens had a ratio of >1.0.

Mean root depth to radial root lateral spread (d/ls) was calculated for 136 forb specimens. The d/ls ratio was 2.3. Fifty per cent of the specimens had a 1.0-2.0 d/ls ratio.

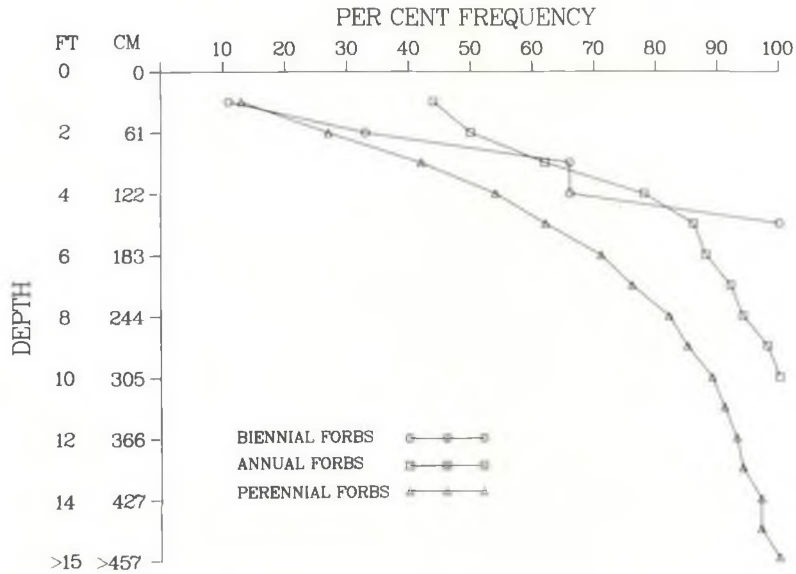

Fig. 4. Cumulative per cent frequency of rooting depth of forbs.

The mean radial root lateral extension to shoot height ratios (ls/h) was 2.0. Fifty percent of the 34 specimens had a ls/h ratio of 1.0-2.0.

7. Perennial Grasses. Perennial grasses are found to root an average depth of 140 cm with a range of 5 to 823 cm. The reference to the deepest rooting species, alkali sacaton [*Sporobolus arioides* (Torr.) Torr.], was based on known water-table levels (823 cm). The best excavation data were based on information by Tomanek and Albertson (1957). They found blue grama [*Bouteloua gracilis* (H.B.K.) Griffiths] and side-oats grama [*Bouteloua curtipendula*) (Michx.) Torr.] to root to depths of over 400 cm.

Rooting depth frequencies are shown in Fig. 5. The highest rooting frequencies were at 91 cm. Median rooting depth is 106 cm. Less than 1% rooted at depths greater than 457 cm.

The average lateral extension for perennial grasses is 60 cm (Table III).

8. Annual Grasses. Rooting depths of a total of 8 native annual grasses and 16 domestic crop species were recorded. The average rooting depth for the native species is 52 cm with a range of 5 to 110 cm. Three-awn (*Aristida oligantha* Michx.) and downy chess (*Bromus tectorum* L.) are the deepest rooting species. Domestic species root from 122 to 223 cm with an average rooting depth of 170 cm. Domestic species include oats [*Avena sativa* (L.) Theu.], wheat (*Triticum*) spp., and barley (*Hordeum vulgare* L.).

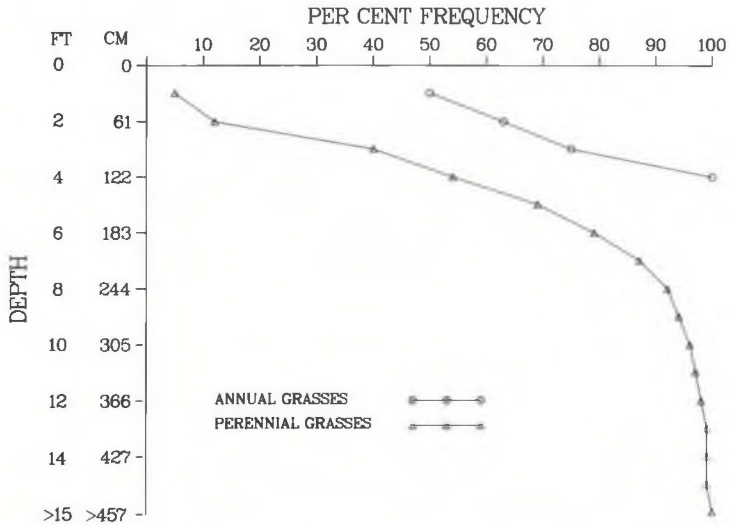

Fig. 5. Cumulative per cent frequency of rooting depth of grasses.

Rooting depth frequencies are shown for native species in Fig. 5. The highest frequency of rooting depths is at 30 cm. All specimens rooted in the first 91 cm. The median rooting depth is 30 cm.

Mean root depth to shoot height (d/h) measurements were calculated for 10 grass specimens for which data had been found. The d/h ratio was 2.0 (Table II). The highest ratio was for mountain muhly. Fifty percent of the specimens had a >1.0 ratio.

Mean root depth to radial root lateral spread (d/ls) was calculated for 45 grass specimens. The mean d/ls ratio was 1.8 (Table II). The highest ratio was for *Aristida purpurea* Nutt.; the lowest for *Agrostis alba* L.

Mean radial root lateral extension to shoot height (ls/h) of 2.7 was calculated for 10 grass specimens. The highest ls/h ratio was 3.7, while the lowest was 0.16.

9. Vines. Rooting depths were recorded for only four vines. The average rooting depth is 168 cm with a range of 102 to 280 cm (Table I). No recorded vine root depth exceeds 457 cm.

10. All Vascular Plants. Depth information was recorded on 1012 vascular plants. The rooting average for all the life forms is 190 cm with a range of 2 to 6096 cm. The rooting frequencies (Fig. 6) show that the

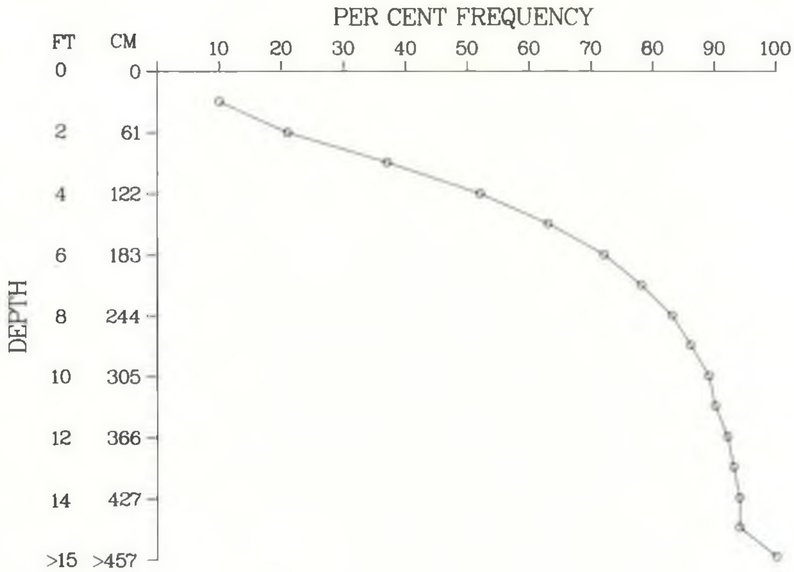

Fig. 6. Cumulative per cent frequency of rooting depth for 1012 vascular plants.

highest percentage of species root to 91 cm. The median rooting depth is 122 cm. Only 6% of all the specimens studied rooted deeper than 457 cm.

11. Cumulative Frequency for Different Life Forms in the Data Base. Table IV summarizes the accumulative rooting depth frequency of nine life

TABLE IV

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

forms for five selected depths: 91, 183, 274, 366, and 457 cm. The shallowest rooting life form is annual grass. If overburdens are 91 cm deep, the roots of these specimens will be confined to that zone. All other life forms root deeper than 91 cm. On a percentage basis shrubs root the deepest, followed by deciduous and evergreen trees.

B. Soil Type

Substrate information was recorded for over 600 specimens. There was little consistency in soils data; over 300 distinct types were recorded. Therefore, all soil types were categorized as to texture: per cent sand, per cent silt, and per cent clay. Each entry was placed under one of the five categories (adobe clay, loam, clay loam, sand, and silt) using a guide for textural classification.

1. Adobe Clay. Of the 82 specimens found to root in clays, adobe clays, or hardpan, 48% root at 30 cm or less. Cumulative frequencies (Fig. 7) show 50% root at greater than below 61 cm. Only 1% root to depths greater than 457 cm. Lateral extensions of 78% of all the specimens rooting in adobe clay are 91 cm, but 7% have roots extending 457 cm from the shoot (Fig. 7).

2. Loam. Of the 134 plants that root in loams (Fig. 8), 44% root to only 91 cm. No specimen roots below 305 cm. Lateral extensions in loams are

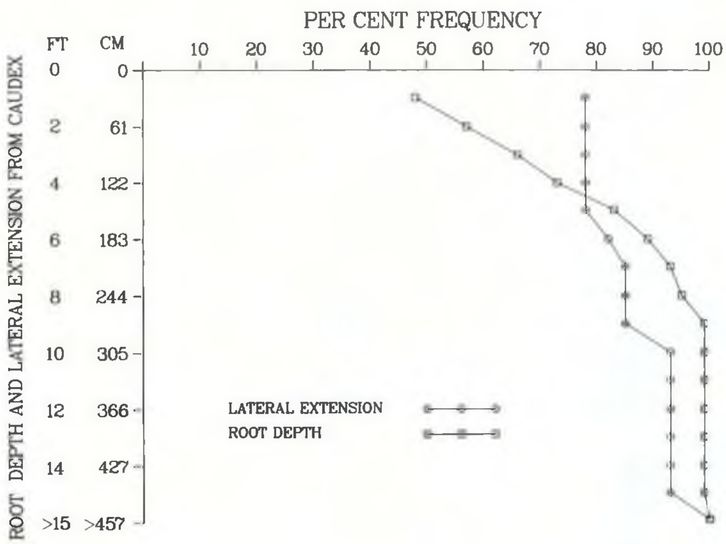

Fig. 7. Cumulative per cent frequency of rooting depth and lateral extension of plants growing in adobe clay.

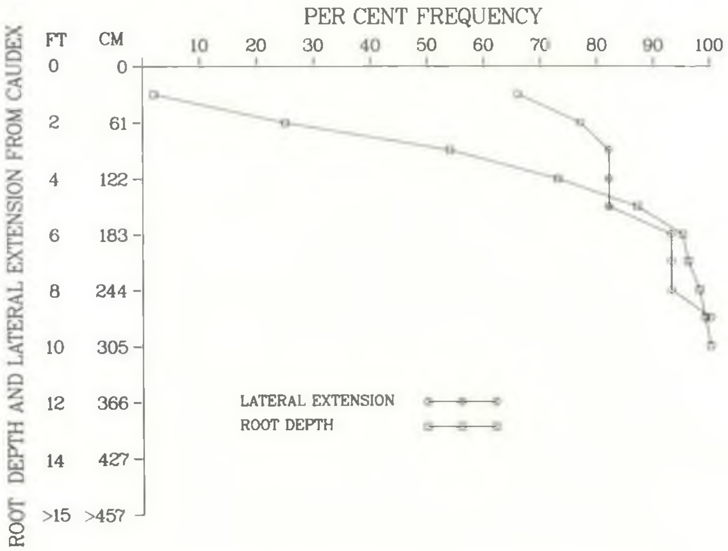

Fig. 8. Cumulative per cent frequency of rooting depth and lateral extension of plants growing in loam.

no more than 274 cm. Over 80% of all specimens recorded had lateral extensions of 91 cm or less.

3. Clay Loam. Of the 65 specimens rooting in clay loams (Fig. 9), 48% root to 122 cm. Only 1% of specimens rooted to depths greater than 457 cm. Average length of laterals is less than 91 cm.

4. Sand. Of the specimens rooting in sands, 56% root deeper than 91 cm. Average lateral extensions from the caudex were to over 457 cm 30% of the time (Fig. 10). A total of 58% of all specimens have lateral extension in the first 91 cm.

5. Silt. Of the 150 plants rooting in silt, loess, and silt loam (Fig. 11), 50% root less than 152 cm in depth. Only 3% root at depths greater than 457 cm. Lateral extensions can extend beyond 457 cm, but 60% of all specimens extended out only 91 cm.

There seems to be little specific information as to the rooting depth within various soil types. Biswell (1935) observed that root penetration was greatest in loess and lateral spread was greatest in clays. This is not substantiated by the analysis of information in this data base. In this study (Tables V and VI), adobe clays limited both root depth and lateral

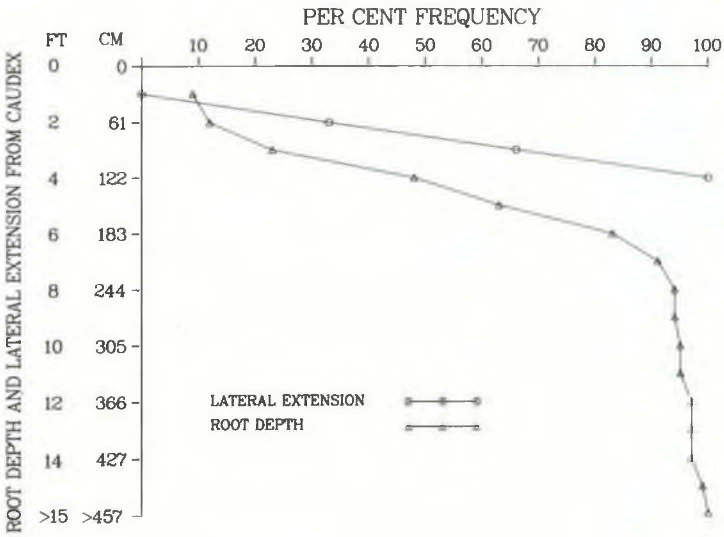

Fig. 9. Cumulative per cent frequency of rooting depth and lateral extension of plants growing in clay loam.

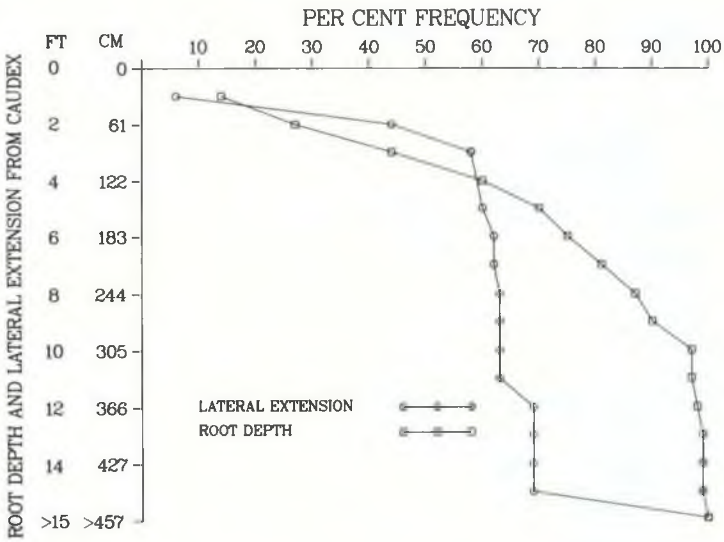

Fig. 10. Cumulative per cent frequency of rooting depth and lateral extension of plants growing in sand.

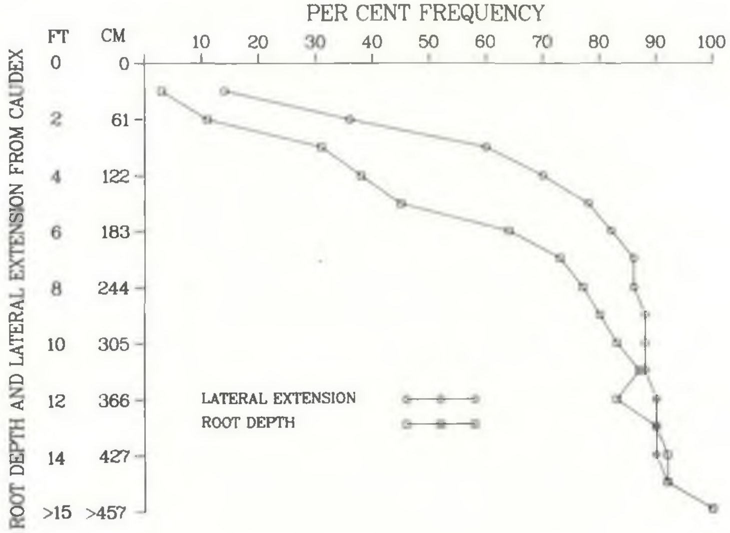

Fig. 11. Cumulative per cent frequency of rooting depth and lateral extension of plants growing in silt.

TABLE V

CUMULATIVE ROOT DEPTH FREQUENCIES (%)
FOR FIVE SOIL TYPES AT SELECTED DEPTHS

Soil Types	Root Depth				
	91 cm	183 cm	274 cm	366 cm	457 cm
Adobe clay	66	89	99	99	99
Loam	54	95	99	100	
Clay loam	48	83	94	99	99
Sand	44	76	90	98	99
Silt	31	64	80	83	93

growth, whereas silts allowed roots to grow to great depths and lengths from the caudex.

Plants growing in adobe clays were found to have the most limited root penetration, and the loams have the highest percentage of lateral roots within 91 cm of the caudex. Clay soils have larger percentages of soil particle sizes below 0.002 mm or 2 μm. Roots have difficulty penetrating spaces of

TABLE VI

CUMULATIVE FREQUENCY (%) OF RADIAL ROOT LATERAL EXTENSION FROM THE CAUDEX

	Length from Caudex				
Soil Type	91 cm	183 cm	274 cm	366 cm	457 cm
Clay loam	61	100			
Loam	81	93	100		
Adobe clay	78	82	86	93	93
Sand	58	62	62	69	69
Silt	60	82	88	90	92

0.1 mm (Russell and Russell 1973, Wiersum 1957); therefore, clays impede both downward and lateral growth of roots. Clays also have a high water-holding capacity, small pore size, and poor aeration (Wiersum 1957), making it difficult for roots to survive at depths. Although the highest percentage of roots are within the upper layers of clay soils, small percentages are found at extreme depths and at long distances from the caudex. Clay soils, when dry, tend to crack and the roots then can follow cracks either vertically or horizontally. This is reflected in the data as a small percentage of the specimens that root deeply or extend large distances from the caudex.

Loams have high percentages of sand, silt, clay, and organic matter. Such soils are high in nutrients, have good aeration, and are generally considered ideal for plant growth. In this study the rooting depth was within the first 274 cm and lateral extensions from the caudex were no more than 274 cm. Weaver and Clements (1938) found roots were shorter in concentrated nutrient solutions. The shallowness of rooting in loams compared with sands or silts may be a function of good aeration and availability of nutrients and water. In such soils, deep rooting is not necessary for plant survival.

Clay loams have a higher percentage of clay and are stickier in texture. They have a higher water-holding capacity than loams. If clay contents are high, aeration may be poor. Rooting in such soils may also be affected by the aggregation; large pores will result in good aeration, thus limiting root penetration. For the most part, these soils may be nutrient poor, thus roots may penetrate deeper. In this data base the rooting depth frequency was greatest within the first 183 cm. Lateral extensions from the caudex were no more than 91 cm.

Based on the literature reviewed, the rooting depth was more limited in sand than in silt, but the percentage of lateral extensions beyond 457 cm is greater in sand. Silts have roots throughout profiles from a few centimeters to many meters. Likewise, lateral extensions in silts were from a few centimeters to many meters. Sands have very high conductivity of water but poor levels of plant-available water. Silts, on the other hand, have a matrix that moves water downward but also provides good water availability throughout the profile. Thus, it is expected (and found) that silts provide the best medium for root penetration.

C. Evaporative Regions

The states can be divided into six regions as related to evaporation and precipitation (Figs. 12 and 13). Precipitation levels in various areas are given in Fig. 12. Region 1 (Fig. 13) has evaporation much in excess of precipitation with an annual rainfall of 0 to 25 cm. Region 2 has evaporation considerably in excess of precipitation with an annual rainfall of 25 to 51 cm. Region 3 has evaporation in excess of precipitation with rainfall averaging 51 to 76 cm. Region 6 has precipitation generally in excess of evaporation and an average annual rainfall of 127 to 152 cm. Rooting information was recorded for all regions except Region 6.

Rooting frequencies are shown for Regions 1, 2, and 3 (Fig. 14). Although 75% of the specimens recorded rooted at 92 cm or less for Region 1, a few were recorded at rooting depths greater than 457 cm. These were trees and shrubs rooting through cracks in clay soils or in fractured rock in mine tunnels. A rough relationship between rooting depths and evaporative regions occurs. Region 1, the driest, had the most shallowly rooting species, with Regions 2 and 3 being similar. Soil type may have an influence because of

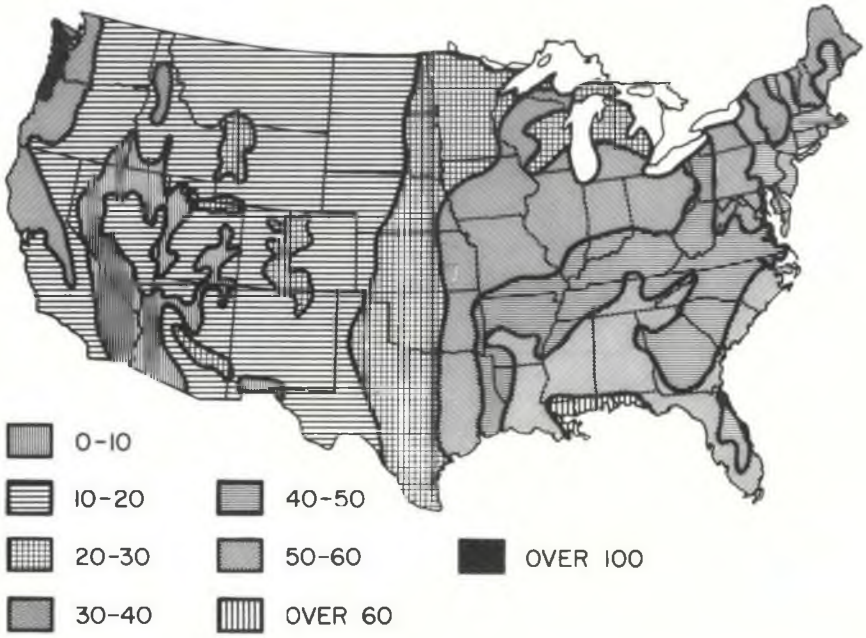

Fig. 12. Precipitation regions (ranges are in centimeters).

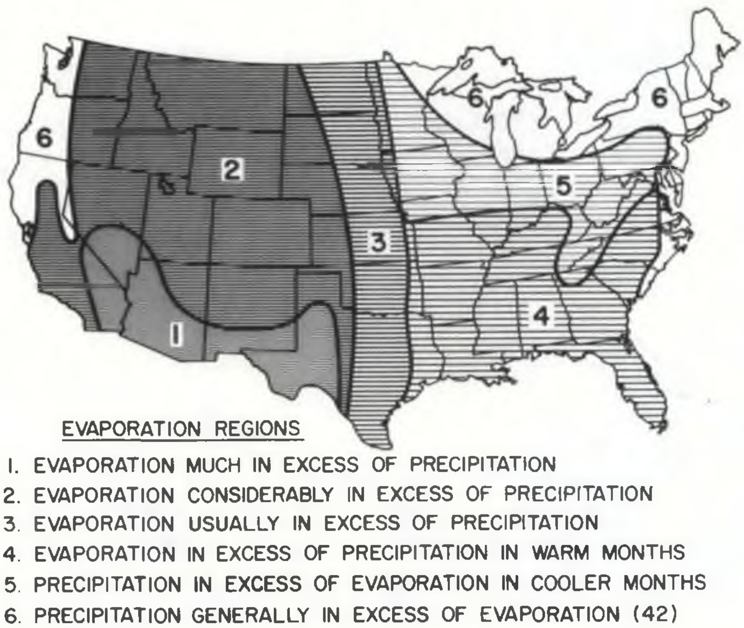

Fig. 13. Regions of evaporation in relation to precipitation.

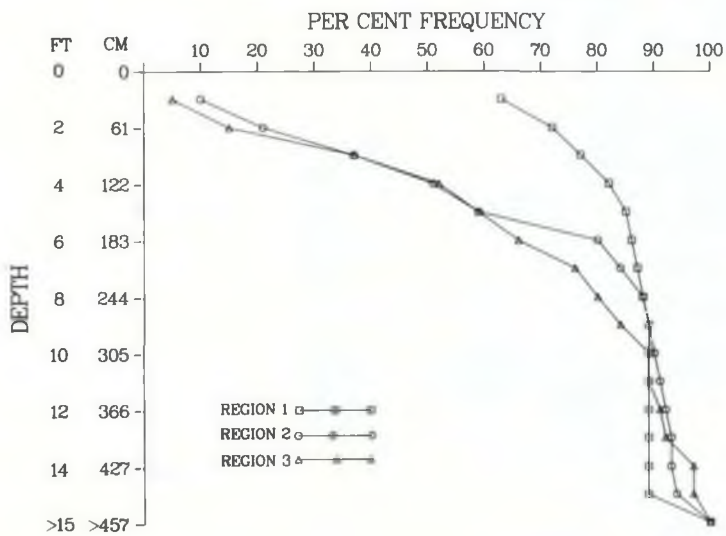

Fig. 14. Cumulative cumulative frequency of rooting depth of plants as related to evaporative regions.

soil development processes due to interaction of climatic variation and soil hydrologic properties. Specimens recorded in Region 1 were primarily associated with adobe clay soils, which cause very shallow rooting. Soils in Regions 2 and 3 were more varied.

D. Root Type

Roots can be classified as either fibrous or taproots. Fibrous roots are generally characteristic of graminoids (grasses and grass-like plants) and taproots of plants in the subclass Dicotyledonae (dicots). In addition to roots, stems are sometimes modified to underground structures for food storage. Such structures are either rhizomes, corms, or bulbs. These organs produce roots from the lower surface and shoots from the upper surface.

Taproots may be fleshy or woody. They arise directly from the seed, then may branch, forming laterals. Fibrous roots are secondary roots that do not arise directly from the seed. In production of fibrous roots, the primary root grows from the seed and absorbs nutrients and water, then fine branches develop as secondary roots that take over these functions as the primary root dies; in some plants the primary root may remain functional. Because of the large amount of branching, fibrous roots are often matlike or hairlike (Cannon 1949, Sutton 1969).

Rooting frequencies were calculated for the fibrous and taproots (Fig. 15). Accumulative frequencies show that 41% of all specimens with fibrous

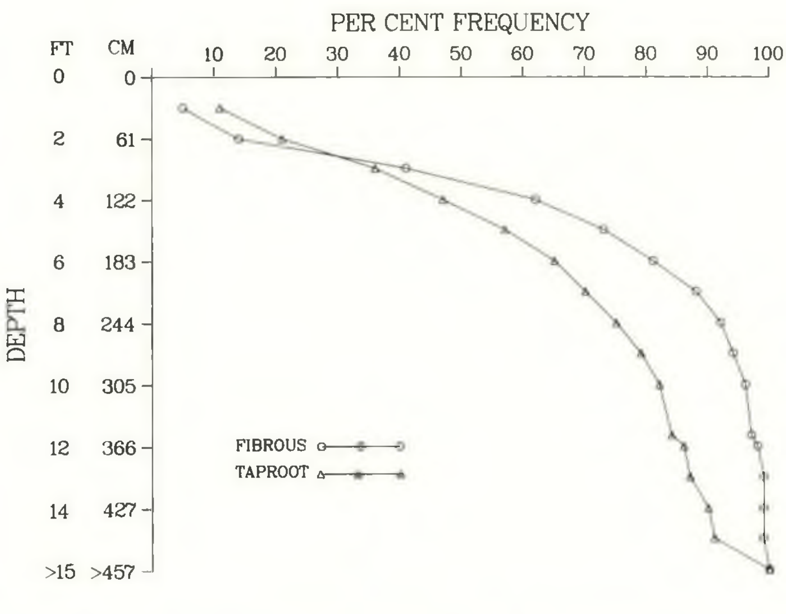

Fig. 15. Cumulative per cent frequency of rooting depth of plants as related to root types.

roots rooted within the first 91 cm compared with 36% for taproots. A total of 81% of all specimens with fibrous roots rooted within the first 183 cm as compared with 65% for taproots. In general, fibrous roots were more shallowly rooted than taproots. Median rooting depths were 103 and 128 cm, respectively. Rhizomes, corms, and bulbs are more shallowly rooted than are fibrous-rooted plants or plants with taproots (Table VII).

IV. SUMMARY AND CONCLUSIONS

There are 11 LLW sites in the United States, 6 of which are found in semiarid or arid regions. Overburdens at most of these sites are 0.3 to 1 m deep. The shallowness of the cover almost assures penetration by the roots of all but the shallowest rooting plants. Indeed, in our study only annual grasses root entirely within 1 m and only half of these root within 0.3 m. Median rooting depths of other life forms are up to 1.95 m with maximum rooting depths to 61 m: annual forbs (median of 0.61 m, maximum of 3.0 m); biennial forbs (0.76 m, 1.5 m); perennial grasses (1.06 m, 8.2 m); perennial forbs (1.14 m, 39 m); subshrubs and vines (1.16 m, 6.4 m); trees (1.58 m, 1.5 m); and shrubs (1.95 m, 17 m). Without effective biobarriers, approximately 1.5 m of cover is sufficient to prevent root entry into the waste, provided the deep-rooting plants are kept cleared.

Cover type strongly affects root penetration and hence the amount of cover needed. Adobe clay affords the shallowest rooting system (median root depth of all plants is 0.4 m; 99% root depth to 2.7 m only 1% at greater depths); sandy soil next (0.75 m, 4.5 m); loam next (0.85 m, 3.0 m), clay loam next (1.3 m, 4.5 m); and finally silt (1.6 m, >4.5 m). Soil effects on lateral root growth are similar except that sandy soils are less restrictive and more like silts. Adobe clay retards root growth by physical restraint, but roots can penetrate through cracks. Sand retards root growth by acting as a sieve to conduct water away before the plants can utilize it.

Root type plays a major role in a plant's ability to penetrate into a soil. Bulb-type roots are the least penetrating (average depth of 0.12 m);

TABLE VII

AVERAGE ROOTING DEPTH BY ROOT TYPE

Root Type	Number	Average (cm)	Sigma (cm)
Fibrous	265	130	88
Taproot	498	245	444
Rhizome	5	80	82
Corm	2	24	5
Bulb	4	12	2

corm roots next (0.24 m); rhizome roots next (0.80 m); fibrous roots next [1.3 m average, 1.0 m median, and 4.0 m maximum (99%)]; and taproots the most penetrating (2.4 m average, 1.3 m median, and >4.5 m maximum).

Plant height can give a rough estimate of root penetration. In most cases, the depth to height ratio (d/h) for trees was less than 1.1. Trees that were less than 305 cm tall had a 0.22 ratio. Shrubs had a d/h ratio of 1.2; forbs 1.7; and grasses, 2.0. In some cases lateral spread may be important, particularly for species on waste site perimeters. With sufficient lateral extensions, species may penetrate wastes from the waste pit exterior. Ratios indicate that the lateral spread of trees will vary with age of the trees. Younger trees will have lower d/ls ratios than will older trees. Shrubs have d/ls ratios of less than 1, forbs and grasses greater than 2. The highest d/ls ratios were found for subshrubs.

ACKNOWLEDGMENTS

The authors would like to thank Wayne R. Hansen, Group Leader, HSE-8, Los Alamos National laboratory, for his support and guidance throughout the project. We also thank Thomas Hakonson, John Nyhan, and Jay Wenzel, Los Alamos National Laboratory, for critical review of the paper. We thank Ili Chen for preparing illustrations and Kathy Derouin for typing the manuscript.

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*U.S. GOVERNMENT PRINTING OFFICE: 1984-0-576-034/4210