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Rooting Depths of Plants on Low-Level Waste Disposal Sites

Teralene S. Foxx*
Gail D. Tierney*
Joel M. Williams

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*Collaborator at Los Alamos.

Los Alamos National Laboratory
Los Alamos, New Mexico 87545

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by

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ABSTRACT

In 1981-1982 an extensive bibliographic study was done to reference rooting depths of native plants in the United States. The data base presently contains 1034 different rooting citations with approximately 12 000 data elements. For this report, data were analyzed for rooting depths related to species found on low-level waste (LLW) sites at Los Alamos National Laboratory. Average rooting depth and rooting frequencies were determined and related to present LLW maintenance.

The data-base was searched for information on rooting depths of 53 species found on LLW sites at Los Alamos National Laboratory. The study indicates 12 out of 13 grasses found on LLW sites root below 91 cm. June grass [Koeleria cristata (L.) Pers.] (76 cm) was the shallowest rooting grass and side-oats grama [Bouteloua curtipendula (Michx.) Torr.] was the deepest rooting grass (396 cm). Forbs were more variable in rooting depths. Indian paintbrush (Castelleja spp.) (30 cm) was the shallowest rooting forb and alfalfa (Medicago sativa L.) was the deepest (>3900 cm). Trees and shrubs commonly rooted below 457 cm. The shallowest rooting tree was elm (Ulmus pumila L.) (127 cm) and the deepest was one-seed juniper [Juniperus monosperma (Engelm) Sarg.] (>6000 cm). Apache plume [Fallugia paradoxa (D. Don) Endl.] rooted to 140 cm, whereas fourwing saltbush [Atriplex canecens (Pursh) Nutt.] rooted to 762 cm.

I. INTRODUCTION

Interest about root penetration into the soil comes from, firstly, the proposed Nuclear Regulatory Commission standards for disposal of low-level nuclear waste (Nuclear Regulatory Commission 1982). Those standards would require design operations that prevent intrusion or disruption of a disposal site for at least 500 years without the need for relying upon institutional monitoring and maintenance of the disposal site after 100 years. The second impetus was the proposed Environmental Protection Agency standards for remedial action at inactive uranium processing sites (Environmental Protection Agency 1983). These standards would ensure that barriers on mill tailing impoundments would be effectively minimized for 100 years with active maintenance, at least 200 years without maintenance, and for 1000 years when reasonably achievable. Substantial earth cover could be penetrated by the roots of native and introduced plants. In fact, investigations into the control and isolation of buried wastes and mill tailing 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).

Intrusion by deeply rooted plants must be assessed in terms of the evolving successional patterns following disturbance of the site. These successional patterns can only be predicted on the basis of site-specific information regarding present species composition, inferred climax species composition, and species morphology. In regard to waste management, root morphology, size characteristics, and physiological activities of successional or selected species are important. Plants, through interception of rainfall and evapotranspiration rates, are important to water balance of the trench cap and the prevention of percolation through the cover. Trench cap engineering is necessary to develop biobarriers to prevent deep-rooted successional species from penetrating the cap, entering the waste zone, and providing a pathway for contamination.

Root ecology studies have provided little succession information regarding plants colonizing or invading burial sites (Whicker 1976, Wyatt et al. 1980). Few root field studies have been conducted since the early, intensive work of Cannon (1911) and Weaver (1915, 1919, and 1926); only a small number of these studies were done in the Southwest (Dittmer 1959, Cannon 1911). Reasons for this paucity of information are evident: root studies are time consuming and labor intensive under field condition, and, until recently, applications of such studies were directed towards using plants as water-source indicators or as water depletors (phreatophytes).

One of the important questions in containment of wastes at low-level waste (LLW) sites and containment of radon on uranium mill tailings is the rooting depth of species that invade or are planted on these sites. At Los Alamos National Laboratory, Tierney and Foxx (1982) did studies to define the

floristic composition as related to time and postclosure patterns of the LLW sites. In a subsequent study,* they determined root depth and morphology of 20 species found on LLW sites at Los Alamos. However, excavating rooting systems is laborious, occasionally hazardous, and time consuming. Therefore, a computerized data base of known rooting depths was prepared at the Los Alamos National Laboratory.**,*** This report summarizes the results of the information from this data base on the rooting depth of species found on LLW sites at Los Alamos National Laboratory and in states west of the Mississippi. The species in the data base are common throughout the arid West (Martin and Hutchins 1981, Kearney and Peebles 1969, Harrington 1964, Abrams and Ferris 1960, and Correll and Johnston 1979), and some are found on other waste sites (e.g., Hanford, Washingtont) and uranium mill tailings (Kelley 1979). Many are components of the native flora that may invade such sites or are recommended species for reclamation (Donovan et al. 1976, Thornburg 1982).

II. 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 the United States in states west of the Mississippi. The information is currently stored in Los Alamos National Laboratory's NOS computer under System 2000. Presently, the data base contains 1034 different rooting citations with approximately 12 000 lines.

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. Twenty-eight data elements were defined. The major elements were family, species, common name, root depth, root lateral extension, root type, shoot height, life form, substrate, geographic location, and reference.

The data base was searched for rooting information related to species known to occur on LLW sites at Los Alamos National Laboratory. When

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*Tierney, G. D. and T. S. Foxx 1983, "A Study of Root Lengths of Some Common Plants that Occur on the Los Alamos National Laboratory Lands". Draft. Los Alamos National Laboratory report.

**Foxx, T. S., G. D. Tierney, and J. M. Williams. 1983. Rooting Depths of Vascular Plants. A Review. (in press).

***Foxx, T. S., G. D. Tierney, and J. M. Williams. 1983. Rooting Depths of Plants Relative to Biological and Environmental Factors (in press).

†Personal communication, William Richard, Environmental Sciences Department, Battelle Pacific Northwest Laboratories. Richland, Washington.

sufficient data (at least six entries) were found for a species, a frequency of rooting depth distribution was calculated. If there was insufficient species data, then data from a plant genera were used when possible. For species with less than six entries, only an average rooting depth was determined.

III. DATA-BASE ANALYSIS

Table I summarizes the site information from the LLW sites at Los Alamos National Laboratory. The oldest site had been decommissioned for 34 years (as of 1981); the newest site 4 years. Site II had the largest numbers of species and was determined to be the closest to climax; whereas, site V is still active and individual pits are closed on a yearly basis. Each site varied considerably in previous history and plant communities. Some were undergoing continual disturbance from burrowing animals creating small microhabitats for disturbed soil plants. As a result, successional patterns were not apparent. Each site was examined for species cover, density, and abundance from which importance values* were calculated. Table II lists all species on the five sites and importance values of 3-61. Species with importance values of <3 are referenced in Tierney and Foxx (1982). Other species were found on the sites, but calculated importance values were less than one; these are referenced in Tierney and Foxx (1982). Floristic data

*Importance values are obtained by adding relative abundance, relative dominance, and relative frequency of each plant and dividing by 3 giving one number for comparison.

TABLE I

SITE INFORMATION ON LOW-LEVEL WASTE SITES AT LOS ALAMOS

Site	Closure Date	Years Since Closure	Number Species	Community Association
I†	1946	34	27, 23	Ponderosa pine; old field
II	1948	32	59	Ponderosa pine
III	1962	18	24	Pinon-juniper
IV	1963	17	29	Ponderosa pine; old field
V†	1976	4	20, 25	Pinon-juniper

†Two separate pits.

from five sites at Los Alamos were examined. The computerized data base was then searched for rooting depths of each species or genus. Table III summarizes the average rooting depth for species found on LLW sites at Los Alamos. Rooting ecology and rooting frequencies of specific species are discussed below.

TABLE III

AVERAGE ROOTING DEPTH OF SPECIES PLANTED ON OR INVADING LLW SITES AT LOS ALAMOS

Species	Common Name	No. in Data Base	Avg. (cm)	Sigma (cm)	Range (cm)
GRASSES					
Koeleria cristata	Junegrass	17	58	31	30- 76
Bromus tectorum	Downy chess	2	70	57	30-110
Festuca spp.	Fescue	19	78	40	5-152
Oryzopsis hymenoides	Indian ricegrass	2	84	54	45-122
Poa spp.	Bluegrass	9	88	54	35-213
Muhlenbergia montana	Mountain muhly	7	91	38	20-135
Sporobolus crypandrus	Sand dropseed	4	99	15	91-122
Aristida spp.	Three-awn	8	108	29	76-152
Stipa comata	Needle-and-thread	10	110	35	63-168
Bouteloua gracilis	Blue grama	29	119	75	38-396
Agropyron smithii	Western wheatgrass	17	148	69	68-314
Buchloe dactytoides	Buffalo grass	17	155	61	46-213
Andropogon scoparius	Little bluestem	10	165	69	71-274
Bromus inermis	Brome grass	3	198	31	168-229
Bouteloua curtipendula	Sideoats grama	6	222	112	76-396
FORBS					
Castilleja spp.	Indian paintbrush	2	28	4	25-30
Mentzelia spp.	Blazing star	3	58	81	11-152
Salsola kali var tenuifolia	Russian thistle	1	67	--	--
Vicia spp.	Vetch	2	80	85	20-140
Hymenoxys richardsonii	Pinque	1	90	--	--
Artemisia frigida	Estafiata	15	104	54	46-244
Potentilla spp.	Cinquefoil	8	110	68	53-229
Amaranthus spp.	Pigweed	3	100	122	10-240

TABLE III (cont)

Species	Common Name	No. in Data Base	Avg. (cm)	Sigma (cm)	Range (cm)
Senecio spp.	Groundsel	5	109	51	30-154
Yucca spp.	Yucca	7	112	74	30-213
Chenopodium album	Lamb's quarters	1	119	--	--
Penstemon spp.	Penstemon	7	129	94	36-305
Melilotus spp.	Sweetclover	3	130	39	85-152
Aster spp.	Aster	5	154	136	15-335
Eriogonum spp.	Buckwheat	9	165	87	64-305
Petalostemon spp.	Prairie clover	4	166	61	85-213
Artemisia dracunculus	False tarragon	1	213	--	--
Kochia scoparia	Summer cypress	1	200	--	--
Oenothera spp.	Evening primrose	5	209	145	53-305
Lithospermum spp.	Puccoon	6	220	71	183-305
Spheralcea spp.	Globe mallow	5	262	147	80-396
Solidago spp.	Goldenrod	9	255	87	107-335
Chrysopsis villosa	Goldenaster	5	275	98	130-396
Haplopappus spp.	Goldenweed	6	287		107-518
Liatris punctata	Gayfeather	6	308	137	120-479
Medicago sativa	Alfalfa	13	690	525	38-3900
SUBSHRUB					
Gutierrezia spp.	Snakeweed	10	122	71	51-244
SHRUBS					
Fallugia paradoxa	Apache plume	2	115	21	60-140
Cercocarpus montanus	Mountain mahogany	4	113	52	40-152
Quercus gambelli	Gambel's oak	2	238	223	80-396
Artemisia tridentata	Big sagebrush	9	248	251	110-914
Chrysothamnus nauseosus	Chamisa	5	293	147	100-457
Rosa spp.	Wild rose	5	391	254	91-640
Atriplex canescens	Four-wing saltbush	3	392	335	110-762
TREES					
Ulmus pumila	Elm	1	127	--	127
Pinus ponderosa	Ponderosa pine	7	447	879	10-2438
Pinus edulis	Pinon pine	1	640	--	640
Juniperus monosperma	One-seed juniper	3	2438	3168	579-6096

A. Grasses

1. Blue Grama (Bouteloua gracilis) (H.B.K.) Lag. This perennial grass had a high importance value on the oldest site (site II) at Los Alamos and was found on all five sites (Table II). It is indigenous in the western United States except for Oregon and Washington; most abundant stands are found in New Mexico and Arizona. These gramas thrive on dry sites below altitudes of approximately 2286 m; they are excellent soil binders but rarely form a complete sod. It is a quick-growing species, maturing in 60 to 70 days, is a normal component of the pinon-juniper woodlands, and is sometimes used to reseed disturbed sites. It has an average rooting depth of 119 cm (Table III), with a range of 38 to 396 cm. The most shallowly rooted representatives are found in loams; the deepest occur in sandy or silty soils. One-half of the specimens recorded have a root depth of less than 91 cm (Fig. 1).

2. Buffalo Grass (Buchloe dactyloides) (Nutt.) Englm. Buffalo grass is a stoloniferous perennial widely distributed in the Great Plains. It is not native to the Southwest but is often used as a component of seed mixtures for site revegetation. In pure stands it forms a close turf. Because it is stoloniferous, it spreads along the soil surface stabilizing and binding the soil. It is drought and cold resistant and poor-soil tolerant. Tierney and Foxx (1982) found this species on sites where it had been used in the seed mixture. Based upon the literature, the average rooting depth was found to be 155 cm, with a range of 46 to 213 cm. The most shallowly rooted specimens were in hard soils or soils underlain with rock or clay; the deepest rooting

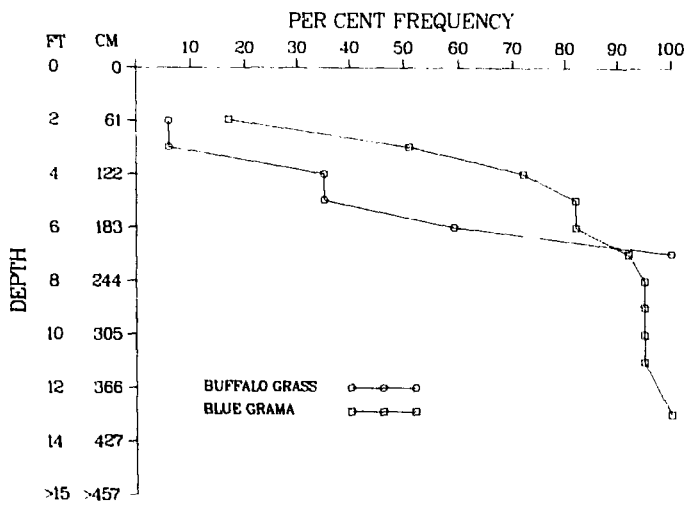

Fig. 1. Cumulative per cent frequency of rooting depths of buffalo grass and blue grama.

specimens were in fine silty soils. Only 5% of the specimens recorded rooted in the first 91 cm, while 59% rooted within 183 cm (Fig. 1).

3. Western Wheatgrass (Agropyron smithii) Rudb. Wheatgrasses are erect perennial bunch grasses widely distributed throughout the western United States. Western wheatgrass is one of the most common and most abundant wheatgrasses. It has rhizomatous rootstocks, is adapted to well-drained areas where other grasses cannot survive, and is often seeded on depleted or disturbed ranges. Western wheatgrass has been a component of the seed mixture on recently decommissioned waste pits at Los Alamos (Tierney and Foxx 1982).

Based upon the available data, western wheatgrass average rooting depth is 148 cm with a range of 68 to 314 cm (Table III). The deepest rooted specimens are in deep silts and sandy soils; the shallowest are found in loams. The median rooting depth is 100 cm (Fig. 2).

4. Little Bluestem (Andropogon scoparius) Michx. The bluestems, or beardgrasses, are a large genus of bunch grasses found in the temperate areas of the world. Little bluestem occurs in every state except those along the Pacific Coast. It is characteristic of tall-grass prairies and is drought resistant. Bluestem does not withstand mowing or grazing well and in overgrazed prairies it is replaced by short-grass species. In the Los Alamos area it is a normal component of the ponderosa pine forests and was found as a native successional species on the higher elevation LLW sites at Los Alamos

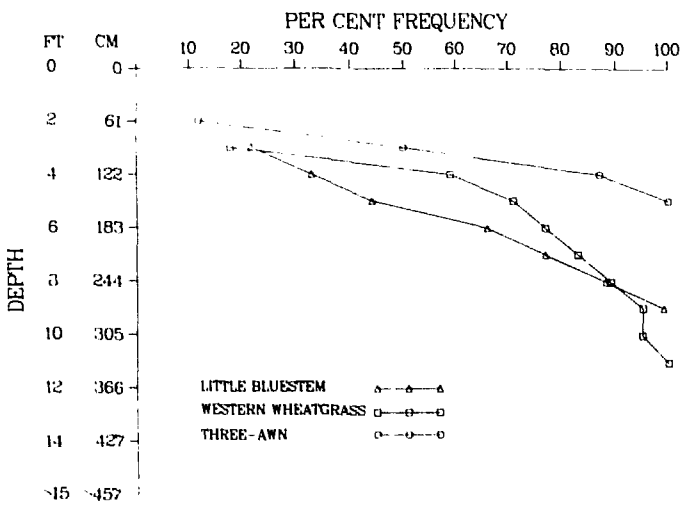

Fig. 2. Cumulative per cent frequency of rooting depth of bluestem, western, wheatgrass and three-awn.

(Tierney and Foxx 1982). Its average rooting depth is 165 cm, with a range of 71 to 274 cm. The most shallowly rooted specimens are found in gravelly soils and soils underlain with rock; the deepest rooting specimens occur in sandy or silty soils. Only 22% of the specimens recorded have roots confined to the first 91 cm (Fig. 2); 44% have roots in the first 152 cm.

5. Three-Awn (Aristida spp.). Three-awns are widely distributed throughout the western United States. They are short-lived species, with seeds well adapted for dissemination. As a result, they rapidly invade disturbed land or depleted ranges. Tierney and Foxx (1982) found this genera invading all five waste sites at Los Alamos. The average rooting depth of these species is 108 cm, with a range of 76 to 152 cm. Half of the specimens root to 91 cm (Fig. 2). The deepest rooting specimens occur in clay loams; the shallowest rooting specimens are found in silt, silt underlain by rock, or sand.

6. Side-Oats Grama (Bouteloua curtipendula) (Michx.) Torr. This is a perennial tufted bunchgrass that is widely distributed from Connecticut to New Jersey to Tennessee, Montana to Utah, California to Texas. In the Southwest it is a grass of dry slopes and rocky hillsides to altitudes of about 2400 m. It grows vigorously, producing large volumes of leafage per plant. Tierney and Foxx (1982) found it on the active LLW site. It was part of the seed mixture for recent reclamation of filled pits. Its average rooting depth is 222 cm, with a range of 76 to 396 cm (Table III). Most occurrences are in silts; the shallowest rooting specimen found was in a silt with underlying rock. This is one of the deepest rooting grass species. It has been found to root to a depth of over 400 cm in prairie soils (Fig. 3).

7. Junegrass (Koeleria cristata) (L.) Pers. Junegrass is a perennial grass that ranges throughout the West, and occurs in Asia and Europe. It is one of the most common and widely distributed western grasses. It is a cool-season grass and a component of ponderosa pine forests and pinon-juniper woodlands. It was occasionally found on LLW sites at Los Alamos (Tierney and Foxx 1982) and has an importance value of <3. The average rooting depth for this species is 58 cm with a range of 30 to 76 cm. Plots of cumulative rooting frequencies show that 100% of all specimens recorded rooted in the first 91 cm (Fig. 3).

8. Mountain Muhly (Muhlenbergia montana) (Nutt.) Hitchc. Mountain muhly is a native bunch grass found throughout the western states between approximately 2134 to 3048 m. Tierney and Foxx (1982) found it as a climax species on older waste sites at high elevations. The average rooting depth is 91 cm, with a range of 20 to 135 cm (Table III). Plots of cumulative rooting frequencies show that 17% of species recorded root in the first 91 cm; the medium value is 106 cm (Fig. 3).

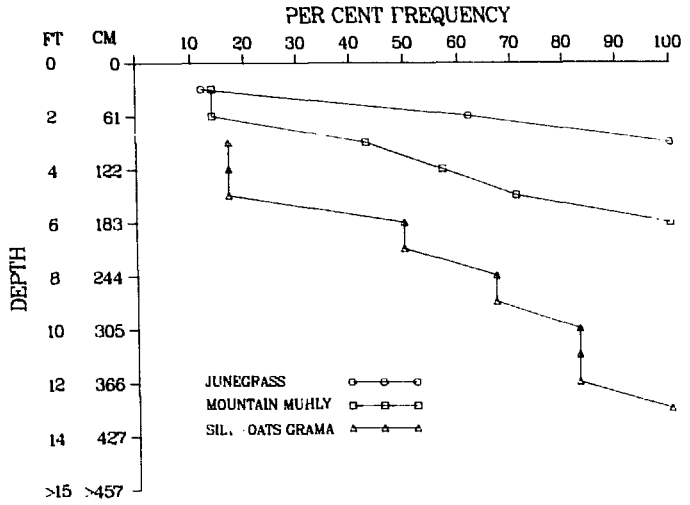

Fig. 3. Cumulative rooting frequency of junegrass, sideoats grama, and mountain muhly.

9. Bluegrass (Poa spp.). Poas are important turf grasses. As native species they are relatively uncommon in the Southwest because of the arid climate. Bluegrass (Poa pratensis) L. requires two or more meters of water per year. This species is found under pinon and juniper canopies where there is shade and increased moisture. Tierney and Foxx (1982) found the species in this genus on two sites; calculated importance values were <3. Average rooting depth for specimens of this genus is 88 cm with a range of 35 to 213 cm. Cumulative rooting depth frequencies show that all specimens root in the first 122 cm (Fig. 4).

10. Fescue (Festuca spp.). Fescues are annual and perennial grasses found throughout the West. Perennials are bunch grasses, and annual species often inhabit disturbed ground. At Los Alamos it was found on one site (Tierney and Foxx 1982). Average rooting depth for this genus is 78 cm, with a range of 5 to 152 cm. Cumulative rooting frequencies show all specimens root within 183 cm, with a median rooting depth of 76 cm (Fig. 4).

11. Needle-and-Thread Grass (Stipa comata) Trin. & Rupr. Needle-and-thread grass is a leafy bunch grass widely distributed across the West to elevations of approximately 2593 m. It is a cool-season grass with leafy foliage that remains green through the summer. Tierney and Foxx (1982) found this species on one site, with an importance value of 3 (Table II). Average rooting depth for this species is 110 cm, with a range of 63 to 168 cm.

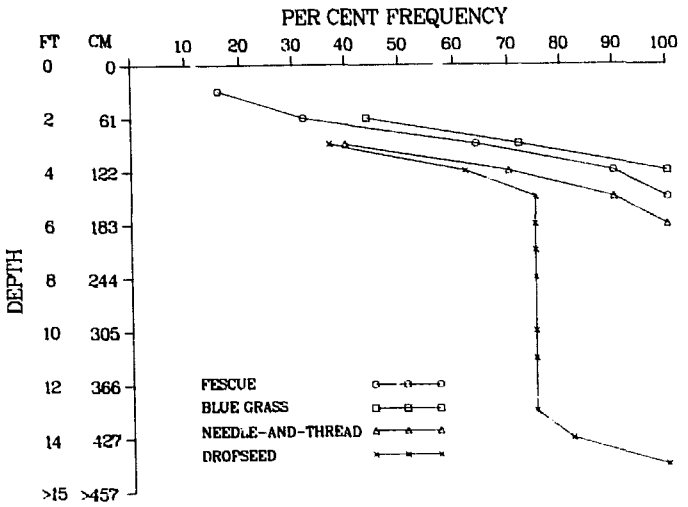

Fig. 4. Cumulative per cent frequency of rooting depths of grasses: fescue, blue grass, needle-and-thread, and dropseed.

Cumulative rooting averages show a maximum rooting depth of 183 cm. The median rooting depth is 100 cm (Fig. 4).

12. Dropseed (Sporobolus spp.). Dropseeds are a large genus of perennial grasses common throughout the Southwest. Species such as sand dropseed [(S. cryptandrus) (Torr.) Gray] are commonly used in revegetation of disrupted sites. Tierney and Foxx (1982) found it as a component of the flora on LLW sites. At more recently closed sites it had been used as part of the seed mixture. There were insufficient data to determine rooting frequencies for sand dropseed alone, so frequencies are based on four species [(S. arioides (Torr.) Torr., S. cryptandrus (Torr.) Gray, S. heterolepis Gray, and S. longiflorus) (Michx.) Kouth]. The average rooting depth for specimens in this genus is 241 cm, with a range of 91 to 823 cm. The median rooting depth was 98 cm (Fig. 4). The deepest rooting specimens, depth to 823 cm and 457 cm, were alkali sacaton; the depths are based on estimation of water-table depth, because these species are phreatophytes. The shallowest specimens are found in silt, sandy loam, and clay loam.

13. Other Grasses. A number of other species including downy chess [(Bromus tectorum) L., Indian rice-grass (Oryzopsis hymenoides) (R.&S.) Ricker, brome grass (Bromus spp.), pine dropseed (Blepharoneuron tricholepsis) (Torr.) Nash, and galleta (Hilaria jamesii) (Torr.) Benth.] were found on waste sites at Los Alamos (Tierney and Foxx 1982), but there were insufficient bibliographic data for rooting frequencies. Average rooting depth for the

first three species are in Table III. No rooting information was found for B. tricholepsis and H. jamesii.

B. Forbs

A number of different forbs were identified by Tierney and Foxx (1982) on LLW sites at Los Alamos. Rooting frequencies of species with six or more entries into the data base were calculated. If there were not sufficient data on an individual species but there were at least six entries within a genus, rooting frequencies were determined for that genus.

1. Fringed Sage, Estafiata (Artemisia frigida) Torr. Estafiata is a semiwoody perennial of the sunflower family. It has a large range, which extends from Mexico to Alaska into Siberia, Northern Asia, and Europe. It is tolerant of moderate shade and moist soils. This species rapidly invades deteriorated ranges and may be an indicator of overgrazing. At Los Alamos it was the most consistently found species on decommissioned LLW sites (Tierney and Foxx 1982) and old fields. Estafiata has an average rooting depth of 110 cm, with a range of 46 to 244 cm. Shallowest rooted species were in rocky soils and loams. Half of the species recorded root in the first 91 cm. No specimen was found to root deeper than 244 cm (Fig. 5).

Other subshrubs or herbaceous plants in the genus Artemisia commonly found on the Los Alamos waste sites included A. carruthii Wood and A. dracunculus L. No rooting depth information was found for the former

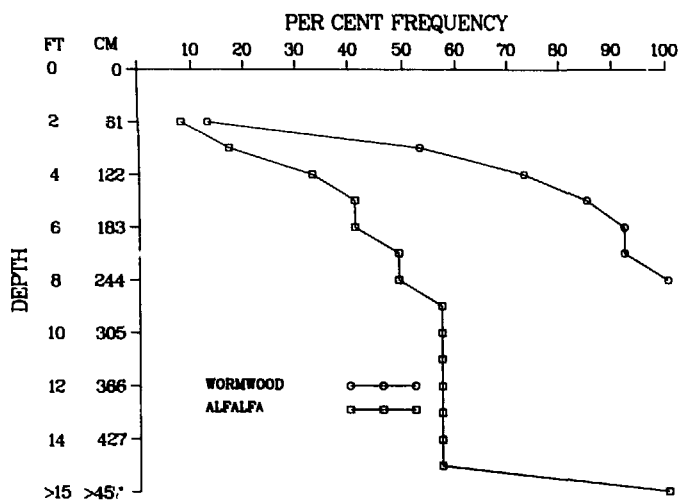

Fig. 5. Cumulative per cent frequency of rooting depths of wormwood and alfalfa.

species, but the latter had one reference indicating root depths to 213 cm in silty soils.

2. Alfalfa (Medicago sativa) L. Alfalfa is a common constituent of seed mixes for reclamation of disturbed lands. It is a valuable forage plant and has been found by Hakonson and Martinez (1982) to attract gophers to LLW sites. It has a large taproot, which has been found at extreme depths (Meinzer 1927). Tierney and Foxx (1982) found it as a component of the flora of recently closed LLW sites at Los Alamos. The average rooting depth is 690 cm, with a range of 38 to 3900 cm. The median rooting depth is 366 cm, with over 43% of the specimens recorded rooting to depths greater than 457 cm (Fig. 5). The shallowest rooting specimens occur in clays, hardpan, or dry soils. Roots were found below 900 cm in cultivated soils. One specimen has been found at more than 3900 cm in a mine shaft where a field of alfalfa existed above (Meinzer 1927).

3. Gayfeather (Liatris punctata) Hook. Gayfeather is a perennial ranging from Idaho to Kansas along the Rocky Mountains into New Mexico. It is a component of the ponderosa pine forest and pinon-juniper woodland and a drought-tolerant species of the sunflower family (Compositae). Windblown seeds allow it to easily invade roadsides and disturbed sites. It was found as an invader on one LLW site at Los Alamos (Table II). The average rooting depth of gayfeather is 308 cm with a range of 120 to 479 cm. The shallowest rooting species occur in loams or loams with clay subsoil. The deepest rooting specimens are found in silty soils or clays underlain by sand. The median rooting depth is 305 cm (Fig. 6).

4. Buckwheat (Eriogonum spp.). Buckwheats rank among the three largest genera of range plants. All species have well-developed taproots and some nodding buckwheat [(E. cernuum) Nutt.] are common on overgrazed or disturbed sites such as the LLW sites at Los Alamos (Tierney and Foxx 1982). Other species are components of the pinon-juniper woodland and ponderosa pine forests. Rooting frequencies were based on data for the following species: E. alatum Torr., E. annuum Nutt., E. flavum Nutt., E. heracleoides Nutt., E. jamesii Benth., E. microthecum Nutt., and E. umbellatum var subalpinum (Greene) Jones. The average rooting depth for the genus was 165 cm, with a range of 64 to 305 cm. A total of 22% of the species in this genus rooted in the first 91 cm (Fig. 6). The shallowest rooting specimens are in dry, rocky soils; the deepest are in loose, coarse granite.

5. Goldenrod (Solidago spp.). Goldenrods are perennial forbs most commonly found in the ponderosa pine forests. Tierney and Foxx (1982) found the genus on old decommissioned sites. The average rooting depth is 255 cm. All specimens root within 335 cm of the surface (Fig. 7).

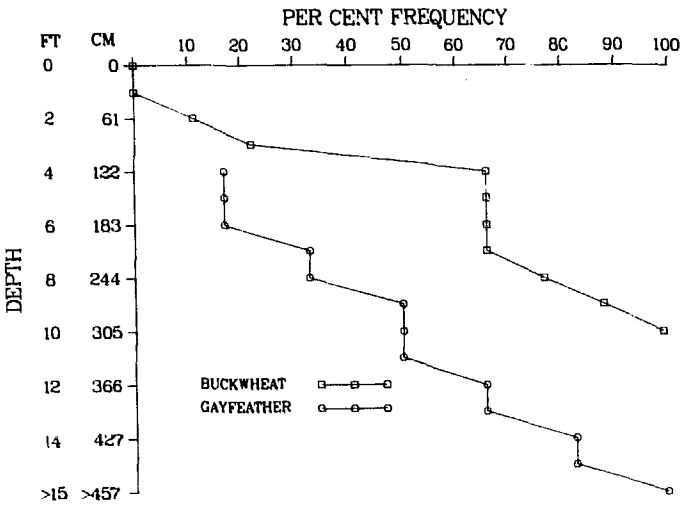

Fig. 6. Cumulative per cent frequency of rooting depths of buckwheat and gayfeather.

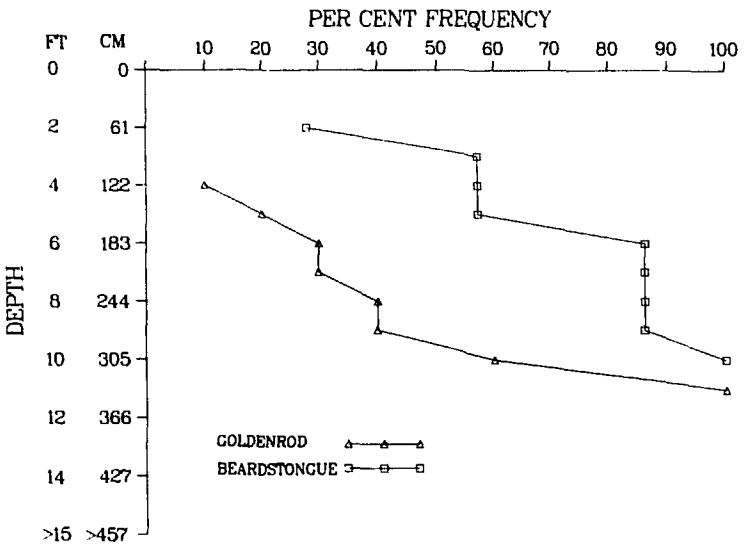

Fig. 7. Cumulative per cent frequency of rooting depths of goldenrod and beardstongue.

6. Beardstongue (Penstemon spp.). Penstemons are common components of a variety of plant communities including disturbed areas. Tierney and Foxx (1982) found these plants on old decommissioned sites closed for over 30 years. The average rooting depth is 129 cm. All specimens root within 305 cm. Half the specimens root within the first 83 cm (Fig. 7).

7. Goldenweed (Haplopappus spp.). Goldenweed is often a component of the flora of disturbed soils. H. spinulosus was found on sites at Los Alamos National Laboratory (Table II). Insufficient data were available for this species; thus rooting frequencies were determined for the genus from H. spinulosus (Pursh) DC., H. racemosa (Nutt.) Torr., H. lanuginosus Gray, and H. lanceolatus (Hook) T. & G. The average rooting depth for this combination of species is 287 cm, with a range of 107 to 518 cm. Fifty percent of the specimens root within the first 183 cm (Fig. 8). The deepest rooting specimens are in silt loam, the shallowest in loess soils underlain by rock.

8. Cinquefoil (Potentilla spp.). There are 110 species of cinquefoil found in the West. Their habitat varies from dry sandy soils to wet meadows. Some species such as P. anerina L. and P. pulcherrima Lehm. are abundant in overgrazed or disturbed lands (Tierney and Foxx 1982). Calculated importance values for potentilla on the Los Alamos LLW sites were <3. Rooting frequencies for this genus are based on rooting information on P. concinna Richards., P. diversifolia Lehm., P. gracilis Dougl., and P. pennsylvanica L. (Fig. 8). The average rooting depth for these specimens with a range of 53 to 229 cm is

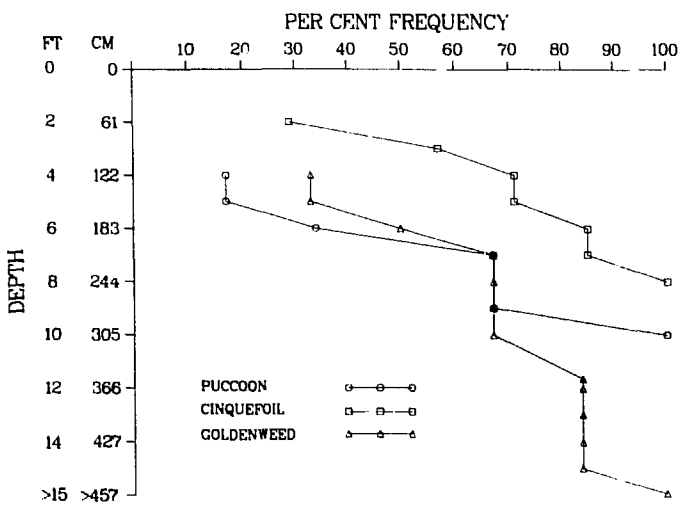

Fig. 8. Cumulative per cent frequency of rooting depths of puccoon, cinquefoil, and goldenweed.

110 cm. The deepest specimens root in silt loam, the shallowest in loam. Th shrubby potentilla (P. fruticosa) L. was found to root to 300 cm in gravelly soils.

9. Puccoon (Lithospermum spp.). Puccoon is a perennial forb found in pinon-juniper woodlands and ponderosa pine forests. Tierney and Foxx (1982) found L. multiflorum Torr. on two waste sites; calculated importance values were <3. Rooting frequencies are based on rooting information for L. caroliniense, (Walt.) MacM. L. incisum Lebm., and L. ruderale Dougl. The average rooting depth for the genus is 220 cm, with a range of 183 to 305 cm. Fifty per cent of the specimens root in the first 191 cm (Fig. 8). The maxin rooting depth was 305 cm. Deep-rooting specimens were in loose, coarse gran- ite. Shallow rooting specimens were in silt loam.

10. Yucca (Yucca spp.). Yucca is a shrubby perennial forb found through out the arid West. Many species are components of native flora, but in over- grazed or disturbed soils the number may increase. Tierney and Foxx 1982 found large numbers of specimens on one site at Los Alamos. The average root ing depth is 112 cm, with a range of 30 to 213 cm (Fig. 9).

11. Sweetclover, Beeclover (Melilotus spp.). Sweetclovers are biennials introduced from Europe and first reported in the United States in 1739. Sweetclover has been a major forage crop since 1900. Because it is a soil

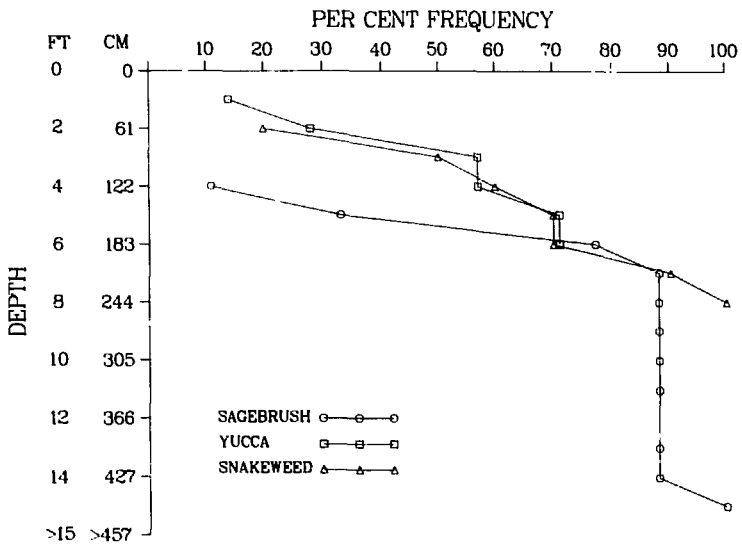

Fig. 9. Cumulative per cent frequency of rooting depths of sagebrush, snakeweed, and yucca.

improver and nitrogen fixer, sweetclover is often used as part of a seed mixture for reclamation of abandoned farmlands, burned-over lands, and LLW sites. Three species are found in the Los Alamos area: white sweetclover (M. albus) Desr., yellow sweetclover (M. officinalis) L. (Lam.), and annual sweetclover (M. indicus) L. (All.). All species are invaders of roadsides and abandoned lands. Tierney and Foxx (1982) found it on all LLW sites, particularly in areas of disturbance. On site V, calculated importance values were <3. The data base contains only three entries, but the average rooting depth is 130 cm, with a range of 85 to 152 cm. The most shallowly rooted species are in hardpan.

C. Shrubs

Three species of shrubs or subshrubs found on LLW sites at Los Alamos had sufficient data for rooting frequencies. The average rooting depth of shrubs for which there were insufficient data to plot rooting frequencies is found in Table III.

1. Rabbitbrush (Chrysothamnus nauseosus) Gray. Rabbitbrush is a rapidly growing shrub that ranges from Wyoming to Nevada and California to New Mexico. It produces numerous windblown seeds that allows it to quickly invade overgrazed lands and disturbed sites. At Los Alamos it was found to root to 180 cm but maximum depth was estimated to be 210 cm based on excavations. Based on the literature, average rooting depth for this species is 293 cm, with a range from 100 to 457 cm.

2. Big sagebrush (Artemisia tridentata) Nutt. Big sagebrush ranges from Nebraska to Montana, British Columbia to California, and into northern New Mexico. It occurs as a climax species and a major part of the plant cover in extensive areas of the arid West. In areas depleted by overuse it becomes an invading species. Tierney and Foxx (1982) found it on one waste site at Los Alamos, but it is also a component of the flora of the area. The average rooting depth is 248 cm with a range of 110 to 914 cm. The median rooting depth is 164 cm (Fig. 9). The deepest rooting specimens were found on the Colorado Plateau in an unknown soil type (Cannon 1960); the shallowest, in clay loam.

3. Snakeweed (Gutierrezia spp.). Snakeweed is distributed throughout the western states between 1200 and 2400 m. It is an invader into overgrazed or depleted ranges. Tierney and Foxx (1982) found G. microcephala [(DC.) Gray] on four LLW sites. Rooting frequencies, however, are based on depth information for G. diversifolia Greene and G. sarothrae (Pursh) Britt. and Rusby. The average rooting depth of this genus is 122 cm within a range of 51 to 244 cm. The median rooting depth is 91 cm with a maximum depth of 244 cm (Fig. 9). Tierney and Foxx (1982) found G. microcephala [(DC.) Gray] rooting to depths of 34 cm in clay loam soils derived from volcanic tuff.

D. Trees

Three tree species [(ponderosa pine Pinus ponderosa Laws, pinon pine Pinus edulis Engelm., and one-seed juniper Juniperus monosperma (Engelm.) Sarg.)] were commonly found in the vicinity of waste sites at Los Alamos and are climax species. Only ponderosa pine had enough entries in the data base to calculate root frequency distributions. Average rooting depths for all tree species found on waste sites at Los Alamos are found in Table III.

1. Ponderosa Pine (Pinus ponderosa) Laws. Ponderosa pine is one of the most common forest trees in the southwestern United States between elevations of approximately 1676 and 2590 m. It is found scattered above and below that elevational range. It often grows in pure stands at about 2438 m and was a component of the flora of old decommissioned sites at Los Alamos. Its average rooting depths is 447 cm, with a range of 10 to 2478 cm. It most frequently roots between 91 to 123 cm. The deepest penetration is in mine shafts (Cannon 1960), where it rooted to 2478 cm.

2. Juniper (Juniperus monosperma) (Engelm.) Sarg. Juniper is a common component of woodlands below 2134 m. It ranges from west Texas to Nevada, Colorado to Arizona, and is the most common juniper in New Mexico. The average rooting depth is 2438 cm, with a range of 579 to 6096 cm. Tierney and Foxx (1982) found this species rooting in cracks in tuff to depths of 6.4 m. It appears to be one of the deepest rooting tree species.

3. Pinon Pine (Pinus edulis) Engelm. Pinon pine is a climax species at 1830 to 2135 m and is a codominant overstory plant at these altitudes. Rooting depths at Los Alamos have been found to 640 cm.

E. Comparison of Rooting Depth of Three Families Commonly Found on Waste Sites

Three families--sunflower (Compositae), pea (Leguminosae), and grass (Graminae)--were compared to determine relative rooting depths. Tierney and Foxx (1982) found these to be the families with the highest importance values on LLW sites at Los Alamos. The pea family had the deepest rooting average (310 cm), then the sunflower family (194 cm), and finally the grass family (134 cm). Rooting frequencies for the three families were compared (Fig. 10). The grass family had the highest frequency of specimens rooting above 183 cm (78%), the sunflower family had 61% of roots above 183 cm, and the legumes had 57% at or above 183 cm. Only 1% of the specimens recorded roots at or deeper than 457 cm; 99% of the grass family rooted to this depth, 93% of the sunflower family, and 90% of the legume family. The deepest rooting representatives of the sunf[illegible] family were shrubs such as sagebrush (Artemisia tridentata) and rabbitbrush (Chrysothamnus nauseosus). The deepest rooting representatives of the legume family were herbaceous forbs such as alfalfa (Medicago sativa).

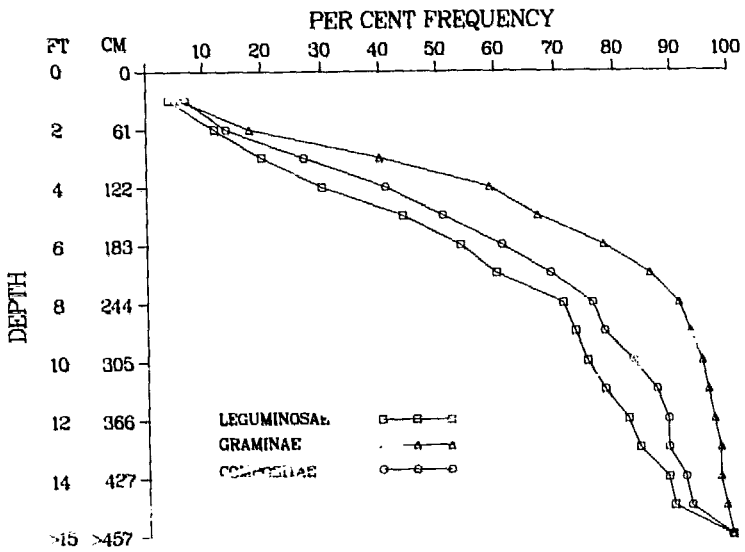

Fig. 10. Comparison of cumulative rooting frequencies for three families of vascular plants commonly found on LLW sites.

IV. DISCUSSION AND CONCLUSIONS

There are six LLW burial sites in arid regions of the United States (Duguid 1977). Surface materials composing the waste site covers include weathered tuff, silty clay, sand, and gravel. Presently, most sites have overburdens of 30 to 91 cm. This study indicates that regardless of soil type, most grass species will root to depths greater than 91 cm, the exception being Junegrass (Koeleria cristata) (Table IV). The shallowest rooting grasses were found to be bluegrass (Poa spp.), fescue (Festuca spp.), three-awn (Aristida spp.), and needle-and-thread grass (Stipa comata). Side-oats grama (Bouteloua curtipendula) and alkali sacaton (Sporobolus arioides) were found to root to depths greater than 457 cm. The majority of the grass species studied root within the first 274 cm.

Forb species were more variable in rooting depths (Table V). Species such as alfalfa (Medicago sativa), gayfeather (Liatris punctata), and goldenweed (Haplopappus spp.) root below 457 cm, while roots of species such as yucca (Yucca spp.) and groundsel (Senecio spp.) are within the first 183 cm. Buckwheat (Eriogonum spp.), wormwood (Artemisia spp.), cinquefoil (Potentilla spp.), and goldenrod (Solidago spp.) do not root deeper than the first 274 cm.

TABLE IV

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		
Little bluestem	22	66	100		
Buffalo	6	59	100		
Wheatgrass	18	77	95	100	
Blue grama	51	82	94	95	100
Dropseed	37	75	75	85	100
Side oats grama	17	50	67	83	100

TABLE V

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

Trees and shrubs commonly root deeper than 457 cm. Roots of shrubs and tree species such as one-seed juniper (Juniperus monosperma) have been found at great depths.

When three families of plants--the grass family, sunflower family, and pea family--were compared, it was found that the grass family rooted the most shallowly and the pea family the deepest. Foxx et al. (1983) have found rooting depth varies with biological and environmental factors, and these should

be taken into consideration when selection of specific species is made for site stabilization.

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