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PLANT SPECIES POTENTIALLY SUITABLE FOR COVER ON LOW-LEVEL SOLID NUCLEAR WASTE DISPOSAL SITES: A LITERATURE REVIEW

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ABSTRACT

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Relevant literature concerning alternative strategies for long-term vegetation management on low-level nuclear waste disposal areas in the White Oak Creek drainage basin within the Oak Ridge Reservation is reviewed. The "ideal" vegetation cover was envisioned as (1) requiring low or no maintenance, (2) having a high water demand, (3) having a shallow root profile, (4) taking up negligible amount of radionuclides, and (5) being capable of successful competition with invading successional species.

Selection of potential species for plot studies has been addressed by discussion and review of numerous species. Conclusions have been drawn from the literature concerning (1) the influence of vegetation on the water balance of the soil when only shallow-rooting vegetation cover is allowed; (2) rooting depth, environmental factors, and succession; (3) maintenance of vegetation; and (4) reevaluation of strategies currently employed.

When roots occupy a soil fully and atmospheric conditions are favorable, plants are able to dry out the root-occupied soil to a water tension of around 1.5 MPa (15 bar) (generally the permanent wilting point). Since rainfall averages 132 cm/year on the reservation, different vegetation types will not have a significant influence on the water balance if only shallow-rooting cover is allowed.

Plant species and varieties have genetically determined root-growth characteristics, which, however, environmental factors may override. Soil moisture, aeration, and bulk density of the soil are determining factors for root penetration. Deeper root penetration can be expected in progressive successional stages. When plants occupy the same site for a longer period of time, roots may penetrate deeper into soil layers. The fraction of the root biomass penetrating deeper soil layers can be physiologically important in water relations and element cycling.

Vegetation that needs the least maintenance is best adapted to the specific environment where it is established. Natural succession is not desirable on the disposal sites because of the deeper rooting of species common to later successional stages. Retaining favored natural successional stages requires maintenance. Broomsedge fields appear to be the most promising. Shrub thickets may not prevent deep-rooting trees from invading the sites.

Literature concerning, roadside vegetation and coal spoil reclamation lists grasses, legumes, shrubs, and trees best suited for these areas. Grasses are either short-lived or need mowing and fertilization. Legumes, such as crownvetch and sericea lespedeza, will form reasonably stable cover, but they develop penetrating taproot systems. Shrub thickets are often nurseries for invading trees.

Horticultural species are more costly to establish and may need periodic weeding, pruning, or pest control.

The present method of maintaining the low-level nuclear waste disposal sites in grass cover probably involves the least risk with regard to root invasion as long as drought-resistant grass species are

INTRODUCTION

The objective of this report is to assess the potential of vegetation cover and of plant species to influence the water balance in the soils over low-level radioactive waste burial sites. The "ideal" vegetation cover would (1) require low or no maintenance, (2) have a high water demand, (3) have a shallow root profile, (4) take up, or "mine," negligible amounts of radionuclides, and (5) be capable of successful competition with invading successional species.

Oak Ridge National Laboratory (ORNL) began operation in 1943. Low-level radioactive wastes have been buried in unlined trenches in designated areas around the laboratory and covered with about 0.6 m of soil since that time. This method of waste disposal potentially allows percolation of precipitation through the waste, leaching of radionuclides, and subsequent lateral groundwater transport from the burial sites (Duguid 1975). Because of the hilly topography, both vertical and lateral water movement need to be considered with regard to radionuclide transport (Arora et al. 1981). To reduce infiltration of water, polyvinyl chloride sheets have been placed over the waste before covering it with soil in some areas, asphalt-lined ditches divert surface runoff in other areas, and elsewhere a compacted bentonite-shale mixture overlain with 60 cm of topsoil has been applied over the wastes (Duguid 1975; Arora et al. 1981).

This report reviews available literature on soil conditions, hydrology, and climatological data and suggests plant species suitable for covering the low-level nuclear waste disposal areas in the White

Oak Creek Watershed within the Oak Ridge Reservation. Literature on naturally invading species and secondary succession, on plant species used for reclamation of coal spoils and roadsides, and on horticultural species is reviewed. The potential of plant species to take up, or "mine," the waste through deep rooting is assessed. The effects of vegetation cover on the water balance in a watershed are reviewed. Several conclusions are presented concerning the management of vegetation cover on low-level solid waste disposal areas.

DESCRIPTION OF THE WHITE OAK CREEK WATERSHED

CLIMATOLOGICAL AND PHYSIOGRAPHIC ASPECTS AND REGIONAL VEGETATION TYPES

The White Oak Creek Watershed is a 1550-ha area within the Department of Energy's Oak Ridge Reservation (DOE-ORR). Located in Roane County, Tennessee, the watershed has elevations ranging from 413 m (MSL) at the crest of Melton Hill to 225 m at the mouth of White Oak Creek during low water-pool level at Watts Bar Lake (McMaster and Waller 1965). The climate is typical of the southern humid Appalachian region and is classified as humid mesothermal [Thornthwaite (1948) as cited in Elwood and Henderson (1975) and DeSelm and Shanks (1963)]. Total precipitation on the DOE-ORR averages around 131 cm, with occasional intense storms (Dahlman 1968a). Tamura et al. (1980) calculate the net precipitation in the White Oak Creek water basin to be 77.7 cm/year (average rainfall less evapotranspiration). Elwood and Henderson (1975) estimate the net input of water into nearby Walker Branch Watershed to be 57.1 cm/year. The difference is accounted for by loss from evapotranspiration, loss in deep seepage, and net change in water storage (Elwood and Henderson 1975) as well as differing record periods used in the analysis.

The topographic position of the White Oak Creek Watershed is east of the Cumberland Plateau, with resultant low average wind speeds, infrequent snow or extreme cold, and increased winter rainfall with cloudiness and fog [Holland (1953) as cited in DeSelm and Shanks (1963)]. Summers are moderately cool and winters mild, ranging from an average July temperature of 25.2°C to an average January temperature of 3.5°C (annual mean 14.5°C) (Elwood and Henderson 1975). The number of frost-free days averages 196 (Swann et al. 1942).

Braun (1950) places the area in the oak-chestnut forest region of the Ridge and Valley Physiographic Province of Fenneman (1938). Forest types range from mesic hardwood associations (*Liriodendron* forest) of coves and valleys, through upland oak-hickory communities, to xeric oak-pine communities occupying ridge sites (Harris et al. 1977).

SOIL CONDITIONS, HYDROLOGICAL ASPECTS, AND RADIONUCLIDE WASTE BURIAL

The watershed contains the following large solid waste disposal areas (SWDAs) at about 245 to 275 m elevation: SWDA No. 3, a 2.8-ha site operated from 1946 to 1951; SWDA No. 4, a 9.3-ha site operated from 1951 to 1959; SWDA No. 5, a 13.3-ha site operated from 1958 to 1973; SWDA No. 6, a 28.3-ha site operated from 1973 to the present (Cerling and Spalding 1980). Two other areas, SWDA No. 1 and SWDA No. 2, are less than 2 ha (Duguid 1975). Approximate sizes and locations of the waste disposal areas at ORNL are shown in Fig. 1.

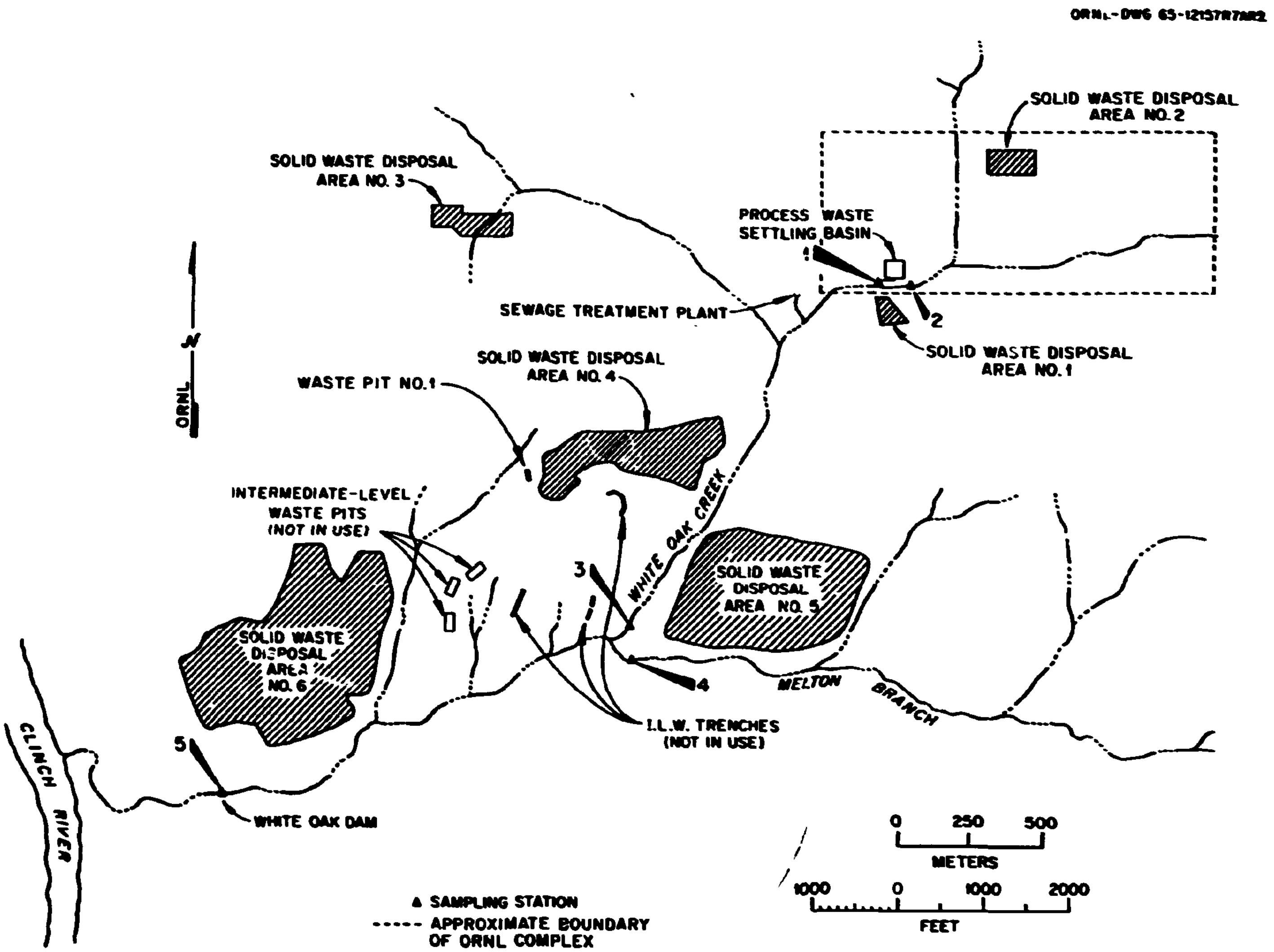

Fig. 1. Approximate location of waste disposal areas and sampling stations at Oak Ridge National Laboratory (from Duguid 1975).

SWDAs Nos. 4, 5, and 6 are underlain by the Middle Cambrian Conasauga Group, which consists of gray calcareous to silty shales interbedded with limestone and siltstone (Fig. 2) (McMaster 1963; Sledz 1980). Weathering depths vary from 1.5 m or less in areas of low topography to as much as 9 to 12 m in the low hills in the area around SWDA No. 6 (Lomenick and Wyrick 1965). Sledz (1980) found that weathering occurred as deep as 30 m in association with higher ridges.

The groundwater table in the White Oak creek drainage basin is a shallow unconfined water table that is a subdued replica of the surface topography. The groundwater flows from high elevations to low elevations where it is discharged into surface streams at or near the stream surface elevation (Duguid 1975). Vertical and lateral water movement should be considered with regard to radionuclide movement (Arora et al. 1981). The waste burial trenches are dug into the Conasauga Shale, which is relatively impermeable. It allows slow percolation of rainfall, with the result that water collects in the covered trenches (Lomenick and Wyrick 1965). Duguid (1975), Meyer (1976), and Wheeler et al. (1976) discuss this "bathtub" effect in the trenches. At SWDA No. 4, shallow asphalt-lined ditches divert part of the surface runoff (Duguid 1975). In three or four trenches at SWDA No. 5, the waste is partly covered with a 2.5-mm-thick polyvinyl chloride sheet with a predicted lifetime of 25 years (installed in 1975) and 0.6 m of soil on top (Duguid 1975; Tamura et al. 1980). Most of SWDA No. 6 is covered with a bentonite-Conasauga Shale seal approximately 7.5 cm thick, with an estimated seal density of 1522 to 1889 kg/m^3 (Arora et al. 1981), which amounts to a bulk density of

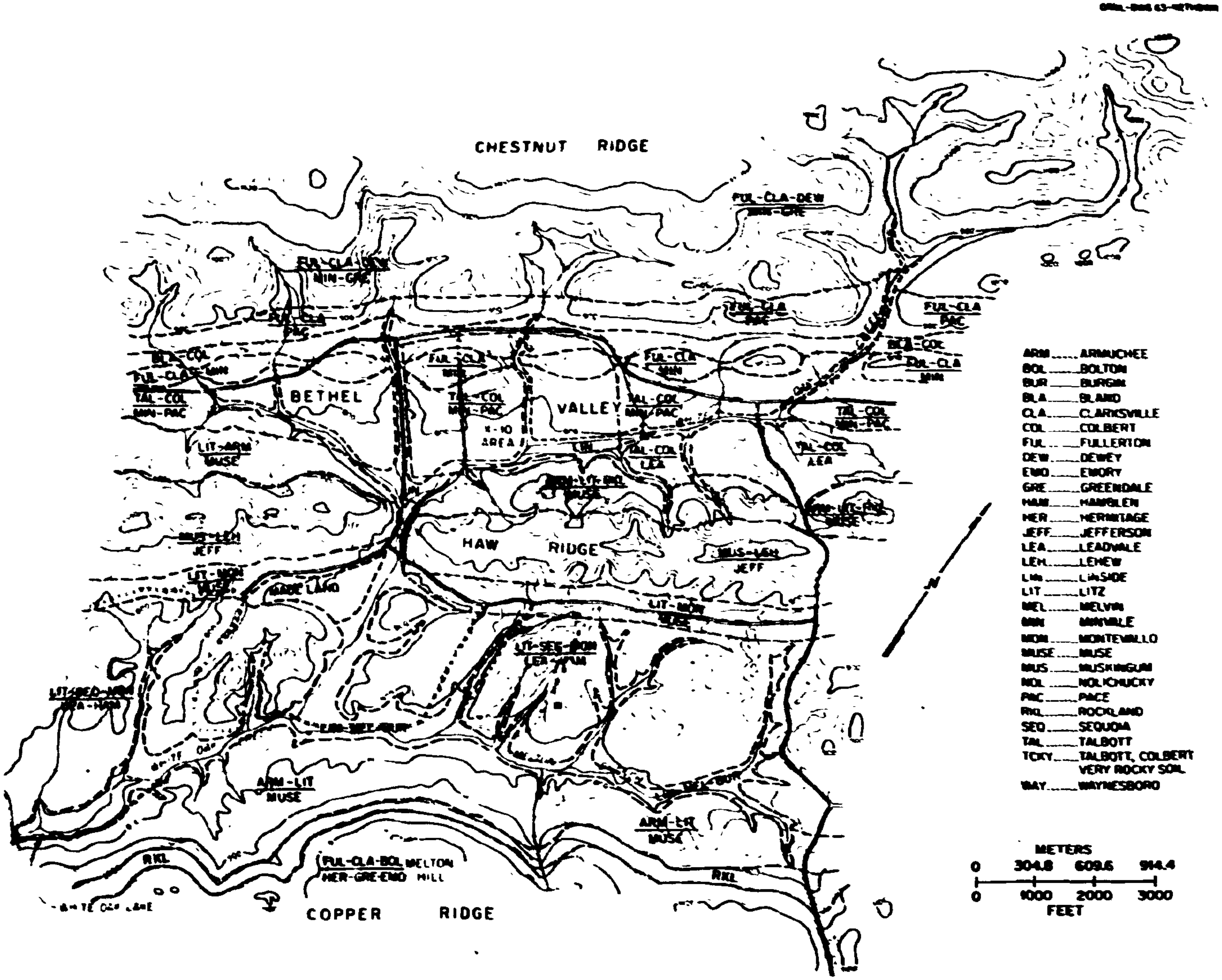

Fig. 2. Soil association map of White Oak Creek drainage basin (from McMaster and Waller 1965).

1.5 to 1.9 g/cm^3. The expected hydraulic conductivity is 2.41 ± 0.33 x 10^{-8} cm/s (n = 3) (Arora et al. 1981), or 0.0021 cm/d. Before waste disposal began at SWDA No. 6, hydraulic conductivity was believed to be 0.15 m/d (Lomenick and Wyrick 1965). The bentonite seal is covered with approximately 0.6 m of soil.

Most of the buried waste is high-bulk, low-density material, which when soaked will collapse and undermine the earthen cap (Meyer 1976), resulting in subsidence of the soil over the trenches (Arora et al. 1981). Duguid (1975) advised volume reduction of the waste material before disposal.

The Conasauga Group overlies the Lower Cambrian Formation. The Rome Formation forms the Haw Ridge just north of the disposal areas. SWDA No. 1 is located in the Rome Formation. The residual soil of the Rome Formation is generally less than 4.6 m thick and is composed of sandy, silty, light-colored clay containing scattered siltstone and sandstone fragments (McMaster 1963).

Copper Ridge, south of the disposal areas, is part of the Lower Ordovician Knox Group, which consists of massive silicious dolomite (Sledz 1980). The Knox Group has weathered to form a deep residual mantle, held in place by abundant chert on the surface, with varying degrees of erosion between formations (McMaster 1963). The Knox Group of Chestnut Ridge north of Bethel Valley is the principal aquifer for the White Oak Creek drainage basin (McMaster and Waller 1965).

SWDAs Nos. 2 and 3 are underlain by Chickamauga Limestone in the southern part of Bethel Valley. Chickamauga Limestone has the least residual thickness (McMaster and Waller 1965).

Swann et al. (1942) mapped the soils of the White Oak Creek Watershed as type 3 soils, characterized by low to very low productivity and unfavorable conditions for workability. This land type consists chiefly of fourth- and fifth-class soils, suitable only for forests. It varies from well-drained acid silt loam to excessively drained, strongly acid, stony fine sandy loam and very fine sandy loam (Swann et al. 1942).

Soils occurring within the White Oak Creek Watershed belong largely to the ultisol and inceptisol orders. In general, these soils are acid in reaction, strongly leached, and low in organic matter and have exchange capacities less than 10 meq/100 g of dry-weight soil (Waller and Olson 1964; McMaster and Waller 1965). The soils derived from Knox Dolomite contain kaolinite as their principal clay mineral; those from the Conasauga Shale contain illite and vermiculite as principal clay minerals. The soils derived from the Chickamauga Limestone contain a mixture of kaolinitic and illitic material, with some units probably having significant amounts of montmorillonitic clay minerals. Percent base saturation varies from less than 10% to greater than 60% (McMaster and Waller 1965).

The soil now covering the waste sites is a mixture of the original top soil and soil dug from the trenches. SWDAs Nos. 2 and 3 have Armuchee-Litz-Muse soil (upland soil of Chickamauga Limestone); SWDA No. 4 has Litz-Montevallo-Muse soil (upland soil of Conasauga Shale and colluvial soil); SWDA No. 5 is surrounded on the east by Litz-Montevallo-Leadvale-Hamblen soil (upland soil of Conasauga Shale, colluvial and local alluvial of Conasauga Shale) and on the south by

Lindside-Melvin-Burgin soils (local alluvial soil and humic gleys); SWDA No. 6 has Litz-Sequoia-Montevallo-Leadvale-Hamblen soil (upland soil, colluvial and local alluvial of Conasauga Shale) (McMaster and Waller 1965). Consequently, natural formations have been destroyed, bulk densities have been altered, and the potential for water infiltration has increased. Eck et al. (1977) found long-term profile modification of clay-loams, accomplished by thorough mixing of soils up to 1- to 1.5-m depths. Effects on water intake rates and reductions in bulk densities were noted for at least the 12 years monitored.

All the sites are maintained as coarse lawn, with a regular mixture of lawn grasses such as Kentucky bluegrass, Kentucky 31 tall fescue, rye, and annual rye. Sites are mowed four or more times a year and fertilized at least once a year (spring and/or fall) (Grizzard 1982).

The water-retaining power of a soil is determined by its texture, structure, and organic matter content (Weaver 1926). The water available from the soil (1) determines the potential for plant growth, (2) is nearly independent of the properties of the plant and (3) is almost entirely governed by those of the soil [Briggs and Shantz (1914) as cited in Kramer (1949)].

Among the herbaceous plants of the humid regions, those restricted to permanently moist sites can lower the water potential of roots to, at most, -1 MPa (-10 bar); plants growing in dry areas, to as much as -6 MPa (-60 bar); crop plants achieve -3 MPa (-10 to -20 bar); for forest trees, the limit is considered to be -3 MPa (-30 bar) (Larcher 1980).

Ideally, the following characteristics of a soil to be revegetated should be considered: soil origin, soil texture (percent sand, silt, clay) and structure, consistency, bulk density and pore space (both large and small pores), moisture-holding capacity at various tensions and percolation rates, soil strength, soil color (which indicates the degree of aeration and drainage of the soil), pH, organic matter content, available phosphorus, exchangeable cations (potassium, calcium, magnesium), cation-exchange capacity of the soil, nitrogen levels, predominant clay minerals, and slope and exposure of the land.

MAINTENANCE OF VEGETATION COVERS

NATURAL VEGETATION

Ecologists, horticulturists, and agronomists recognize that plants grow best when they are well adapted to their environment and, consequently, require less maintenance:

> Sometimes the best choice for waste areas or wild places, where no special maintenance can be given, are the plants native to the area (Atkinson 1970).

> The use of native vegetation for indicating possibilities of growth (of crops) has proved very valuable in those areas where it has been most fully studied (Weaver 1926).

> Knowing the principles of succession, it should be obvious that the simpler form of management would be one that least modifies the natural development of vegetation (Oosting 1953).

> No (right-of-way) vegetation management is possible without knowledge of the "flora" of the region (the flora being defined as the native and naturalized plants of the region) (Egler and Foote 1975).

> There are no "how to do it manuals" for managing right-of-way vegetation. Vegetation types (that will occur in rights-of-way) are remarkably variable and even unpredictable (Egler and Foote 1975).

McIntosh (1980), in a review article on the relationship between succession and the recovery process in ecosystems, says that Egler essentially argues that an established vegetation cover resists invasion from the outside and that even artificial seeding does not readily displace established vegetation. Egler's example is the clearing of a 64-km fire-line plot in two forest communities in southeastern New York. A cleared strip of land, 12 m wide and 6100 m long, was studied. It had been stable for a period of 15 years in the form of a naturally established shrub-herb community and was not expected to destabilize (Pound and Egler 1953).

One of Egler's warnings against costly vegetation management is: "Do not plant shrubs, for nature plants cheaply and horticultural shrubs need careful attention" (Egler and Foote 1975). He points to the understory of the forests surrounding a future right-of-way as a possible source of vegetation for the future right-of-way. Soil type, drainage, elevation, and the vegetation's tolerance of sunlight will be determining factors as to what type of brush will maintain itself.

In considering vegetation cover for waste disposal areas, maintenance and stability must be taken into consideration as well as rooting depth and the potential effect on the water balance of the soil.

BALDS, BARRENS, AND GLADES

Balds, barrens, and glades are considered to have reasonably stable vegetation. Important species of these community types are summarized in Table 1. (Common names of species are listed in Appendix A.) In the southern Appalachian Mountains, naturally occurring grass balds are

Table 1. Important flora of balds, barrens, and glades

Southern Appalachian grass balds (Mark 1958)	
Danthonia compressa	Rumex acetosella
Potentilla canadensis	
Southern Appalachian mixed heath balds (Whittaker 1963)	
Clethra acuminata	Rhododendron catawbiense
Gaylussacia baccata	Rhododendron maximum
Kalmia latifolia	Vaccinium constablaei
Pyrus melanocarpa	Viburnum cassinoides
Rhododendron carolinianum	
Oak Ridge area barrens (DeSelm et al. 1969)	
Agave virginica	Lonicera sp.
Andropogon gerardi	Panicum stipitatum
Andropogon scoparius	Pinus sp.
Andropogon virginicus	Rosa sp.
Juniperus sp.	Salix nigra
Central Tennessee basin cedar glades (Quarterman 1950)	
Aristida longespica	Petalostemum sp.
Celtis laevigata	Rhus aromatica
Erigeron strigosus	Sporobulus sp.
Forestiera ligustrina	Symphoricarpos orbiculatus
Juniperus virginiana	Ulmus alata
Missouri Ozark glades (Kucera and Clark 1957)	
Accacia angustissima var. hirta	Panicum virgatum
Andropogon gerardi	Rhus aromatica
Andropogon scoparius	Sorghastrum nutans
Bouteloua curtipendula	Sporobolus heterolepis
Ceanothus ovatus	Symphoricarpos orbiculatus
Juniperus virginiana	

confined to a relatively narrow altitudinal band around 1500 m (Mark 1958). Mark found a high proportion of weedy species, both naturalized and indigenous, on the balds. Periodic droughts and changing intensities of grazing are considered primary factors responsible for vegetation changes on the balds over time (Mark 1958).

Mixed heath balds in the southern Appalachian Mountains occur at elevations between 1400 and 1700 m. Some species occurring on these balds extend down to the lowest elevations, around 460 m, in the mountains (Whittaker 1963).

DeSelm et al. (1969) describe the barrens of the Oak Ridge area in Tennessee as physiognomically and floristically similar to the barrens and "cat-prairies" of Kentucky and southern Ohio, and somewhat less like the prairies of the central United States. In their sampling of 14 old fields, thickets, and barrens over bedrock Chickamauga Limestone, they found successional stages prolonged by edaphic factors. The most stable barrens were controlled by shallow, droughty soils (DeSelm et al. 1969). They related the high frequency and cover of broomsedge to mowing of broomsedge fields.

On Lebanon Limestone in the central basin of Tennessee, the major plant communities are the cedar glades (Quarterman 1950), which begin with bluegreen algae and lichens as pioneers, followed by succulents and mosses. After accumulation of organic matter and soil, the deeper soil is invaded by herbs and, in turn, by shrubs and trees.

In the little bluestem-dominated glades of the Missouri Ozarks, the mean annual rainfall is 112 cm, soil depths vary from 0 to 46 cm, and vegetation is grazed. Other grasses that dominate within the glades are summarized in Table 2. Contrasting rooting depths of these grasses are listed for mixed and tall grass prairie.

Rhus glabra, *Symphoricarpos orbiculatus*, and *Corylus americana* invade upland prairie where little bluestem is the major grass species. The ability of these shrubs to form underground stems from which roots extend downward to depths of 2 to 2.5 m is an important competitive advantage of these species (Weaver and Kramer 1932). Little bluestem is accompanied by big bluestem and Kentucky bluegrass (*Poa pratensis*). The grass roots in the upland prairie rarely reach beyond 0.9 to 1.5 m deep, whereas accompanying forbs root as deep as 2.5 m and even 3.7 m. The underground stems of the shrubs may form shoots that will eventually form a closed canopy and shade the grasses (Weaver and Kramer 1932).

Table 2. Rooting depth of prairie grasses

Species	Root depth (m)	Prairie type	Reference
Andropogon scoparius	0.9-1.7	Tall grass	Weaver 1926
Andropogon gerardi	2.7	Tall grass	Weaver 1926
Bouteloua curtipendula	1.4-1.7	Mixed and tall grass	Weaver 1958
Panicum virgatum	2.4-2.7	Tall grass	Weaver 1926
Sorghastrum nutans	0.9-1.7	Tall grass	Weaver 1926
Sporobolus heterolepis	1.2-1.5	Upland	Weaver 1958

SUCCESSION AND HABITAT CHANGES

Edaphic factors, periodic droughts, grazing, mowing, and fire are some of the factors influencing the stability of a vegetation. Consideration of pertinent old-field succession studies might indicate other factors that play a role in the successful competition of vegetation covers with invading species.

Keever (1950), in analyzing causes of old-field succession, points to (1) the time of year at which seeds mature and germinate, and the relationship between the time of seed germination and the time at which secondary succession is initiated as crucial factors in determining the initial species composition of secondary succession; (2) the distance to seed sources; (3) seed size and seed dispersal mechanisms; (4) inhibiting effects of decaying roots on establishment of seedlings of the same species [e.g., horse-weed (Erigeron canadensis)]; (5) light requirements of species [because shading by mature plants can prevent establishment of seedlings of the same species, as in broomsedge (Andropogon virginicus) and others]; (6) drought resistance of established and invading species; and (7) organic matter accumulation in the soil.

Odum (1960a) found no organic matter buildup in the soil during the first 3 years of succession in one study. Changes in soil characteristics appear to be unrelated to loblolly pine succession in abandoned fields (Coile 1940). Sassafras, black locust, and pines contribute significantly to restoration of soils on abandoned fields in the form of litter buildup and improved surface soil infiltration rates and improved soil structure (Auten 1945). In comparison to soils used for agriculture or pasture, Wood (1977) found lower bulk densities and greater porosity in forest-covered soils. Billings (1938) reported a significant correlation between the amount of organic matter in the surface soil and the number of oak seedlings in old-field succession. Studies of the interactions between organic matter, nitrogen, inorganic mineral particles, and aggregates in soil are suggested by Cromack (1981) as important considerations in understanding changes in soil organic matter and nitrogen in different stages of succession.

Soil type (noneroded phase) was shown to have little influence on the sequence or duration of early stages of succession (Keever 1950). Odum (1960a) confirmed that soil type had little influence on species composition in the first year of secondary succession. During the second and third years, however, species composition showed marked differences on different soil types, a divergence that increased for the next several years. He found that many species appeared sooner on heavier soils, whereas certain species were virtually restricted to specific soil series.

Fuller (1914) and Gleason and Bates (1912) measured evaporation rates at about 20 to 25 cm above the soil surface across different vegetation types and found that the highest evaporation rates occurred where there was the least vegetation. Weaver (1941) found evaporation rates greater in pasture than in prairie. Fuller considered the progressive increase of air moisture with progressively denser vegetation in the 20- to 25-cm stratum above the soil a critical point for succession, because in that stratum seedlings develop and the succeeding vegetation depends on their survival and eventual death.

Golley and Gentry (1966) emphasize Oosting's (1942) point that in small fields succession may be very rapid, while in very large fields succession may be arrested by a temporary stable adjustment of species variety and rate of net production. As an example, Golley (1965) suggests that a 121-ha field of broomsedge (Andropogon virginicus) may require 25 years before transition into the next successional stage, pine, which occurred in 5 to 10 years in 4- to 10-ha fields described by Oosting (1942).

Connell and Slatyer (1977) discuss succession and recognize three successional models from the literature. The "facilitation" model claims that later successional species become established only after earlier ones have suitably modified the conditions. The "tolerance" model claims that later successional species become dominant because they can grow at lower levels of resources than can earlier ones, with or without the presence of earlier successional species. The "inhibition" model claims that no species has competitive superiority over another; invasion is possible only if the new colonist has adaptive resources, such as deep roots or large seeds, so that seedlings can be sustained until energy is released through damage to, or death of, a previous competing occupant. Species composition of the "inhibition" model will shift toward species that live longer. Connell and Slatyer (1977) consider "climax" species those species most resistant to damage or elimination. If individuals are likely to be replaced by a member of their own species, the stability of the species is better ensured (Connell and Slatyer 1977).

Monk (1966) considered the relationship between root growth and shoot growth an important aspect of succession. He showed that mean root-to-shoot biomass ratios increased from annuals to herbaceous perennials to woody perennial seedlings (pines and hardwoods as separate groups). Biennials and loblolly pine seedlings (Pinus taeda) had root-to-shoot ratios that overlapped with those of herbaceous perennials. On abandoned farmland in the eastern deciduous forest, succession typically passes through stages dominated in sequence by annuals, herbaceous perennials, pines, and hardwoods (Monk 1966). Succession from annuals to herbaceous perennials may be partially due to the increase in root proportion, while the replacement of herbaceous perennials by pines may be related to the larger stature of pines, since the root-to-shoot ratios for herbaceous perennials and loblolly pines are in some cases equal. The ability of hardwoods to develop in pine forests may be enhanced by their larger root system. Weaver and Kramer (1932) considered the initial rooting habit of an individual tree the determining factor in survival or death of a seedling and gave the example of bur-oak (Quercus macrocarpa) seedlings with a rooting depth of 0.9 m in the first year. Pines [rather than hardwoods such as sweet gum (Liquidambar styraciflua)] become established as the first woody perennials because establishment of sweet gum is more dependent on moisture. Bormann (1953) found marked differences in the ability of the pine and sweet gum seeds to germinate after drying. First-year loblolly pine seedlings endured drought better than first-year sweet gum seedlings. Harper (1977) points out that plants grown at high stocking density or in the shade adjust their root-to-shoot ratio in favor of shoots, and quotes Milthorpe's (1961) general principle: "The greater the amount of leaf growth made before plants come into contact with each other, the more extensive is the root system and the less likely is the plant to suffer from drought."

Kozlowski (1949), in discussing regeneration of pine stands in the Piedmont, reports that the growth rate of pines is closely related to shading. At low light intensities (shade), root growth of pines will be limited and less water absorbed. Root growth of oaks in relation to top growth is much greater than that of pines, irrespective of light, in soils with adequate moisture and in soils deficient in moisture (Kozlowski 1949). The deep tap roots of oak (*Quercus* sp.) and hickory (*Carya* sp.) enable them to extend below the horizon of most intense root competition (Coile 1940). The root systems of young oak, hickory, tulip-poplar (*Liriodendron tulipifera*), and red cedar (*Juniperus virginiana*) are deep and well developed (Billings 1938). Bard (1952) observed an increase in general depth of penetration of roots with an increase in time after abandonment of fields in New Jersey, a reflection of the increased percentage of woody species in the flora. Even when the flora remains unchanged, deeper root penetration occurs over time. Long (1959) reported deeper root penetration in a fescue-white clover (*Festuca-Trifolium repens*) field at 4 years when compared to 2 years before.

Although root biomass increases with age (Hermann 1977), root-to-shoot production ratios of species decrease with age in general for herbaceous species (Bray 1963). In the seedling stage of herbaceous and woody plants, there is an initial increase in root-to-shoot ratios

(Parsons 1967). However, the fraction of biomass production in roots decreases (with wide differences among species) as the size of woody plants increases from small shrubs to medium-sized trees (Whittaker et al. 1963). Species with a high root-to-shoot ratio may have a greater ability to penetrate hard soil layers (Lyr and Hoffman 1967).

SUCCESSION AND CHANGES IN SPECIES COMPOSITION

Smith (1968), in his study of vegetational stages in five counties near Roane County, Tennessee, summarizes secondary succession as follows: (1) a dominant diverse weedy flora for 1 to 6 years; (2) an Andropogon (broomsedge) stage with considerable floristic diversity until the 14th to 40th year following abandonment; (3) an open, changing to closed, thicket stage dominated by either hardwoods or softwoods; and (4) succession to hardwoods (if it occurs) as early as 90 years.

First-year dominants as described by Smith (1968) were, in order of dominance, Aster pilosus, Erigeron strigosus, Diodia teres, Erigeron canadensis, Solidago altissima, and Plantago lanceolata, all with a cover greater than 5%. The 2- to 6-year dominants were Solidago altissima, Aster pilosus, Gnaphalium obtusifolium, Erigeron strigosus, and Chrysanthemum leucanthemum, each with more than 5% cover. The 7- to 10-year dominants were Solidago altissima, Bromus japonicus, and Andropogon virginicus, with covers of more than 5%. The 10- to 15-year dominant was Andropogon virginicus, with codominants Eulalia viminea and Lespedeza virginica up to a 20-year period. Eulalia viminea retained a high cover in one-third of the stands studied for up to 36 years. Species of the early successional stages are summarized in Table 3.

Table 3. Early secondary successional stages in east and central basin Tennessee

	Smith 1968	Minckler 1946	Quarterman 1957
Pioneer stage			
Ambrosia artimisiifolia var. *elatior*		X	X
Ambrosia trifidia			X
Andropogon virginicus			X
Aristida dichotoma		X	
Aristida oligantha		X	
Aster pilosus	X	X	X
Bromus japonicus			X
Chaerophyllum spp.			X
Chrysanthemum leucanthemum	X		X
Daucus carota		X	
Digitaria sanguinalis		X	X
Diodea teres	X	X	
Erigeron canadensis	X	X	X
Erigeron strigosus	X	X	X
Gnaphalium obtusifolium	X		X
Lespedeza spp.		X	X
Plantago aristita		X	
Plantago lanceolata	X		
Solidago altissima	X		X
Intermediate stage			
Andropogon scoparius		X	
Andropogon virginicus	X	X	X
Aster pilosus			X
Bromus japonicus	X		
Eulalia viminea	X		
Lespedeza virginica	X	X	
Panicum spp.			X
Rubus spp.		X	X
Sassafras albidum		X	
Solidago altissima	X		X
Symphoricarpos orbiculatas			X
Verbesina occidentalis		X	
Final stage			
Succession to closed thicket changing to hardwoods			

Minckler (1946) studied secondary succession plots around Norris, Tennessee. He recognized a pioneer stage lasting from 1 to 6 years after abandonment, with Aster, Diodia, and Erigeron species dominant, but also Ambrosia artimisiifolia var. elatior, Daucus carota, Plantago aristata, Aristida dichotoma, A. oligantha, and Digitaria sanguinalis occurring with Lespedeza sp. in various combinations. Occasionally Lespedeza or Digitaria occurred as premier species. In Minckler's intermediate stage, Sassafras albidum and/or Rubus species invaded and shared dominance with Lespedeza sp., Verbesina occidentalis, Andropogon virginicus, and Andropogon scoparius in various combinations. Later stages were broomsedge (Andropogon virginicus) fields with blackberry and/or sassafras (Table 3).

In a study of two fields dominated by Andropogon virginicus and Festuca elatior, respectively, in Knox County, Tennessee, Harris (1966) observed that Andropogon virginicus shared dominance with Aster pilosus, Solidago altissima, and Panicum commutatum (in terms of over 5% of the total biomass production), while Festuca elatior shared dominance with Solidago altissima and Rubus allegheniensis. Rubus allegheniensis and Lonicera japonica were principal invaders in the fields. Campsis radicans was found in the Festuca community, contributing 4% to the total biomass production.

Kelly (1968) reported on (1) a Festuca elatior var. arundinacea and (2) an Andropogon virginicus dominated field in Roane County, Tennessee. Andropogon virginicus shared dominance with Senecio smallii, Solidago sp., and Lonicera japonica (in terms of over 5% of total biomass production). Festuca elatior shared dominance with Trifolium procumbens, Andropogon virginicus, and Digitatia sanguinalis. Harris (1966) and Kelly (1968) both observed changes over the season with regard to biomass production.

Smith (1968) found Rubus sp. (dewberries including R. enslenii) to occur early in succession together with Smilax glauca. Other Rubus species, such as R. occidentalis, occurred later. Lonicera japonica frequently invaded Rubus patches. Lonicera japonica is characteristic of the grass stage and would often, along with Campsis radicans and Vitis sp., form a distinct stage. Lonicera was reduced during the forest stage because of overstory closure and competition with vines (Rhus radicans and Parthenocissus quinquefolia). In forest stages, the shrubs Hydrangea arborescens and Lindera benzoin occurred on moist sites and Vaccinium sp. and Chimaphila maculata on dry sites as understory (Smith 1968). Early tree invaders were sumac species (Rhus glabra and R. copallina), Sassafras albidum, Juniperus virginiana, Pinus virginiana, and Pinus echinata, with occasional Cercis canadensis, Prunus serotina, Liquidambar styraciflua, and Diospyros virginiana (Smith 1968).

Table 3 also summarizes early successional stages of abandoned croplands in the central basin of Tennessee studied by Quarterman (1957). They were dominated by Erigeron strigosus, Erigeron canadensis, and Ambrosia artimisiiflora var. elatior, with Aster pilosus, Gnaphalium obtusifolium, and Ambrosia trifida codominant the first year (Quarterman 1957). Lespedeza spp. (Lespedeza striata and L. stipulacea) occupied subdominant positions. In the second year, Digitaria sanguinalis was very dense, but Andropogon virginicus became prominent.

In the third year, Aster pilosus and Solidago altissima were considered main dominants, with Chaerophyllum sp. and Bromus japonicus expanding the composition. In later years, Andropogon virginicus and Aster pilosus dominated the fields. Ulmus sp. and Celtis sp. then formed open woods with a herb layer dominated by Andropogon virginicus, Solidago altissima, Aster pilosus, and Panicum spp. Symphoricarpos orbiculatus formed occasionally large thickets. Rubus sp. occurred with a considerable degree of regularity. Maclura pomifera and Cersis canadensis were found occasionally as trees, as was Juniperus virginiana (Quarterman 1957).

A comparison of successional stages studied in Tennessee with those studied in North Carolina and New Jersey, shows there is general agreement (Oosting 1942; Keever 1950; Odum 1960a; Golley 1965; Golley and Gentry 1966; Bard 1952). Broomsedge (Andropogon virginicus) was found to be a major dominant following the forb stage, preceding the invasion of shrubs and trees. Andropogon virginicus occurred with A. ternarius as common species in various ratios, while one or more Andropogon species (A. scoparius, A. virginicus var. abbreviatus, A. elliotti) sometimes showed local dominance (Odum 1960a). Lespedeza cuneata can be an important fall dominant (Golley 1965).

Peak standing crop for broomsedge on abandoned fields in the Piedmont occurred in September and October, while peak production occurred in July (Golley 1965). Golley stated that production in a broomsedge community falls short of the theoretical optimum production calculated from the energy (light) input into the system. He suggested that this inability to capitalize on the available light was due to insufficient interception capacity (surface area of leaf and chlorophyll). Annual net production during the forb stage of old-field succession declined from an initial peak of 500 g m^{-2} $year^{-1}$ to a stabilized rate of 300 g m^{-2} $year^{-1}$. The broomsedge stage had an initial peak of 650 g m^{-2} $year^{-1}$, which declined to 550 g m^{-2} $year^{-1}$ (Golley 1965). Golley expected the broomsedge stage to have an equilibrium level well above the forb stage of succession. Menhinick (1967), studying an 8-year-old Lespedeza cuneata field in South Carolina, found an estimated minimal net community production of 550 g m^{-2} $year^{-1}$ (oven-dry weight). Peet (1981) reports forest production in the North Carolina Piedmont on infertile uplands, characterized by shrink-swell (montmorillonitic) clays, to be as low as 450 g (aboveground oven-dry weight) m^{-2} $year^{-1}$.

McQuilkin (1940) considers the invasion of pines (loblolly and shortleaf) in abandoned fields in the Piedmont neither conditioned by, nor directly related to, the succession of herbaceous plants. When a good seed source is present, favorable weather is prevalent, and fair-to-good site conditions exist in the field, pine reproduction in densities equivalent to 2500 or more seedlings per hectare can be found to distances averaging 100 m from the parent stand. Pines seem fully as capable of colonizing bare areas as the hardiest weeds and may become established on eroded areas in advance of Andropogon, such that the latter is completely shade-excluded from succession (McQuilkin 1940).

Reclamation of Drastically Disturbed Lands

Numerous vegetational species (150) were tested by Springer et al. (1969) over a period of 12 years to determine those best adapted for providing long-term erosion control with the least maintenance. Species requiring minimal maintenance and intermediate (periodic mowing and fertilization) maintenance are summarized in Table 4.

The annual lespedezas (*Lespedeza striata* and *L. stipulacea*) and weeping lovegrass (*Eragrostis curvula*) were found to be well adapted to poor conditions and useful as temporary companion plants, but they were not generally long lived (Springer et al. 1969). To maintain a longer-lasting cover, lovegrass foliage must be mowed, burned, or grazed (Vogel 1981). Vogel (1981) mentions the low cover values of annual lespedezas during winter. Springer et al. (1969) describes Kentucky bluegrass (*Poa pratensis*) as well adapted to urban and park areas when properly managed with white clover (*Trifolium repens*) and when moisture is not a limiting factor and fertilizer is regularly applied, and bicolor lespedeza (*Lespedeza bicolor*) as a warm-season perennial 1.2 to 1.8 m high with a heavy root system well adapted to road sites. Vogel (1981) and others [references cited in Hutnik and Davis (1973) and Schaller and Sutton (1978)] discuss the same species that Springer does as well as additional species for reclamation of coal spoil areas.

One of the main problems in evaluating plant species suited for low-level nuclear waste disposal sites is that little information exists about their potential rooting depth. Table 5 gives an overview of alternative actions or conditions required for the establishment of different vegetation types. The different vegetation types, or rather

Table 4. Vegetation for long-term erosion control (Springer et al. 1969)

Species requiring minimal maintenance:
Andropogon scoparius
Andropogon virginicus
Lespedeza cuneata
Lonicera japonica
Pinus echinata
Pinus rigida
Pinus strobus
Pinus taeda
Pinus virginiana
Pueraria lobata
Robinia pseudo-acacia
Native herbaceous plants
Species requiring intermediate maintenance:
Coronilla varia
Cynodon dactylon
Eragrostis curvula
Festuca elatior var arundinacea
Lespedeza bicolor
Lespedeza stipulacea
Lespedeza striata
Poa pratensis
Trifolium repens

Table 5. Response matrix for establishing vegetation on low-level solid nuclear waste disposal areas[a]

Community types	Response on impact	Water penetration into soils	Erosion prevention	Evapotranspiration potential	Fertilizer requirements	Pruning/clipping	Mowing	Weeding	Organic matter removal	Pest control (herbicide)	Stability of vegetation	Rooting depth
Bare ground		v	l									
Shallow-rooted lawn grass species		l	m	l	h		h		l		m	l
Drought-tolerant lawn grass species		m-h	m	v	h		h		l		m	h
Prairie grass species		m	m	v	l		m		l		m	h
"Natural" grass vegetation: broomsedge		v	m	l-m			m		l		m-h	m
Herbaceous horticultural species		v	v	m	l			h	l	m	m	v
Forbs and weeds		v	m	m							m	v
Low shrub species		v	v	m	l	h		h	l	m	m	v
Tall shrub species		v	v	m	l	h		h	l	m	m	h
"Natural" thickets		v	m	m							m	v
Trees		v	v	h						m	h	h

[a]Magnitude of response: low (l), medium (m), high (h), or variable (v). Responses are species dependent, season dependent and dependent a maturity of vegetation.

plant species constituting the vegetation types, affect the parameters identified with different magnitudes and degrees of importance. Numerical values can be attached to the magnitude and degree of importance in each case. The magnitude of the environmental impact of the different plant species, or vegetation types, will be (1) species dependent, (2) season dependent, and (3) dependent on the maturity of the vegetation type.

Bare ground will be subjected to heavy erosion. Evaporation from a nonvegetated soil surface will be greater than that from a vegetated soil surface, and increased or decreased water penetration will be soil dependent. Puddling of the soils can be expected on the waste sites if they are not covered with vegetation.

Trees may be less desirable as vegetation cover on disposal sites where deep roots may interface with wastes or where the weight of the trees can enhance subsidence of the overburden on the waste sites.

Grass species, when discussed in revegetation and horticultural literature, are often reported to be drought tolerant. Drought-tolerant plant species are considered by many (Burton et al. 1957; Doss et al. 1960, 1962) to be those species that are able to root deeply.

A natural stage in secondary succession in eastern Tennessee is broomsedge vegetation. Broomsedge (Andropogon virginicus) is regarded as shallow rooted when compared to big and little bluestem (A. gerardi and A. scoparius) (Bennett et al. 1978); however, it may be considered deep rooting in some cases (Kelly 1982). Broomsedge grows on soils of extremely low fertility (Bennett et al. 1978) and is established by application of seed-bearing hay as mulch. It may be necessary to till or partially disturb the soil of a field that has succeeded from a previously maintained lawn to produce a receptive seed bed (Vogel 1981). To inhibit invading species, it is necessary to mow the stand once a year after seeds have matured and/or after the application of 2,4-D. Occasional removal of litter buildup will rejuvenate broomsedge vegetation.

The prairie grasses, big and little bluestem in combination with partridge pea (Cassia fasciculata), Indian grass (Sorghastrum nutans), and switchgrass (Panicum virgatum), are suggested by Vogel (1981) for reclamation of coal spoils, with occasional removal of litter buildup to rejuvenate stands. Foote and Jackobs (1966) recommend partridge pea, a summer annual, as a useful species for nonstable sites under adverse conditions because of its ability to form dense stands on previously bare sites. Deertongue (Panicum clandestinum), a perennial warm-season grass appropriate for reclamation of spoils, establishes best when seeded alone (Vogel 1981). Weeping lovegrass (Eragrostis curvula), an introduced warm-season perennial grass, provides good initial cover but is gradually replaced by other perennial species (Vogel 1981). Lawn or agriculturally important grass species considered are summarized in Table 6.

To maintain grass species, mowing or grazing and often fertilization are necessary. Bermuda grass (Cynodon dactylon), an introduced warm-season perennial grass that roots deeply, grows fast, and spreads by underground rhizomes and aboveground stolons (Bennett et al. 1978), is extremely drought tolerant (Weeds, Trees and Turf 1980). Tall fescue (Festuca elatior var. arundinacea), an introduced cool-season perennial (Vogel 1981), is drought resistant, water

Table 6. Lawn or agriculturally important grass species

Genus and species	Common name	Warm season[a]	Cool season[a]	Perennial	Fertile soils	Soils low in fertility	Drought tolerant	Shallow rooted	Rhizomatous/fibrous root system	Clumps or bunch	Creeping habit of growth	Rapid[b]	Moderate[b]	Slow[b]	Comments
Agrostis alta	Red top		X	X		X		X			X	X	X		Does well on acid and poorly drained soils (Bennett et al. 1978); does not persist more than few years (Vogel 1981)
Bromus inermis	Bromegrass		X	X			X		X				X	X	May need nitrogen fertilizer (old stands) (Vogel 1981)
Cynodon dactylon	Bermuda grass	X		X			X		X			X			Must be planted vegetatively with pieces of rhizomes and stolons (Vogel 1981)
Dactylis glomerata	Orchard grass		X	X		X						X	X		
Festuca elatior var. *arundinacea*	Tall fescue		X	X			X						X		Needs good fertilizer program (Bennett et al. 1978)
Festuca rubra	Red fescue		X	X			X								
Festuca rubra var. *commutata*	Chewing fescue		X	X			X								
Lolium multiflorum	Annual rye		X							X		X			Good winter cover (Bennett et al. 1978)
Lolium perenne	Perennial rye		X	X						X		X			Short-lived perennial (Vogel 1981)
Paspalum dilatatum	Dallis grass	X		X	X									X	
Paspalum notatum	Bahia grass			X		X	X								Resistant to weeds (Bennett et al. 1978)
Phalaris arundinacea	Reed canary grass		X	X			X			X			X		Grown on wet areas (Vogel 1981)
Phleum pratense	Timothy		X	X									X		Sow with legumes (Vogel 1981); not adapted to southern regions (Bennett et al. 1978)
Poa compressa	Canadian bluegrass		X	X		X	X							X	
Poa pratensis	Kentucky bluegrass		X	X	X				X					X	
Zoysia japonica	Zoysia grass						X		X						

[a]Season of major growth.

[b]Rate of establishment.

tolerant, and needs a good fertilizer program (Bennett et al. 1978). Chewing fescue (Festuca rubra var. commutata) and red fescue (Festuca rubra), cool-season perennials, are drought tolerant, producing a deep fibrous root system (Bennett et al. 1978). Redtop (Agrostis alba), an introduced cool-season perennial (Vogel 1981), grows well on very acid soils, on clayey soils of low fertility, and on poorly drained soils (Bennett et al. 1978). It is a shallow-rooted grass with both upright and creeping stems (Bennett et al. 1978), but it does not seem to persist for more than a few years (Vogel 1981). Bromegrass (Bromus inermis) is an introduced perennial cool-season pasture and forage grass that is deep rooted and rhizomatous, forming heavy sod (Bennett et al. 1978, Vogel 1981). Old stands may develop nitrogen deficiency, requiring fertilization for maintenance (Vogel 1981). Timothy (Phleum pratense), an introduced cool-season perennial, should be sown with legumes and other grasses (Vogel 1981), but Bennett et al. (1978) claim it is not adapted to the southern region. Orchard grass (Dactylis glomerata), an introduced cool-season perennial (Vogel 1981), will persist and be moderately productive on shallow infertile soils and may become very competitive when sufficient nutrients are available (Bennett et al. 1978). Vogel (1981) considers orchard grass similar to KY-31 tall fescue in growth habit, but generally less persistent where not managed (Vogel 1981). Perennial rye (Lolium perenne) and annual rye (Lolium multiflorum), introduced cool-season grasses (Vogel 1981), are bunch grasses with no creeping habit of growth (Bennett et al. 1978). Annual rye is able to establish a cover for soil protection during the winter in the southeastern United States (Bennett et al.

1978) and can compete with companion perennials (Vogel 1981). Kentucky bluegrass (Poa pratensis), an introduced cool-season perennial (Vogel 1981), does best in highly fertile and productive soils of limestone origin. Bennett et al. (1978) consider it drought tolerant; however, Vogel (1981) does not. Under favorable conditions, it produces a dense rhizomatous sod (Bennett et al. 1978). Canadian bluegrass (Poa compressa), an introduced cool-season perennial, is similar to Kentucky bluegrass, but better adapted to low fertility and droughty soils (Vogel 1981). It is dominant mainly on soils that are acid, droughty, and deficient in nitrogen, phosphorus, or other nutrients (Bennett et al. 1978). Reed canary grass (Phalaris arundinacea), an introduced cool-season perennial (Vogel 1981), is grown in wet areas on disturbed lands. It tends to form clumps and has a dense root system. It is drought tolerant and is able to withstand flooding (Bennett et al. 1978). Dallis grass (Paspalum dilatatum), an introduced warm-season perennial (Vogel 1981), will grow best on moist, fertile, clayey, and clay-loam bottomlands. Bahia grass (Paspalum notatum), an introduced perennial (Hitchcock 1950), grows well on drier soils with low fertility. It is very drought tolerant (Weeds, Trees and Turf 1980), roots deeply, and is resistant to weed encroachment (Bennett et al. 1978). The introduced lawn grass Zoysia japonica forms low-growing dense sods and spreads by rhizomes (Bennett et al. 1978). It is extremely drought tolerant (Weeds, Trees and Turf 1980).

Legumes are often recommended for vegetative reclamation of spoils areas (Table 7). Clover can provide a quick vegetation cover (Vogel 1981), with tap roots penetrating deeply into soils (Bennett et al.

Table 7. Leguminous species recommended for revegetation of spoils areas

Genus and species	Common name	Warm season	Cool season	Perennial	Deep rooting	Rhizomatous	Creeping	Good cover	Low maintenance	Suppresses invaders	Rapid[a]	Moderate[a]	Slow[a]	Comments
Coronilla varia	Crownvetch		X	X		X	X	X	X	X			X	Mowing necessary to control invaders until established
Lathyrus sylvestris	Flat pea	X		X	X	X		X		X			X	
Lespedeza bicolor	Bicolor lespedeza				X									Shrub legume
Lespedeza cuneata	Sericea lespedeza	X		X	X				X				X	Dies back in winter (Menhinick 1967)
Lesedeza japonica	Japanese lespedeza				X									Shrub legume
Lespedeza thunbergii	Thunberg lespedeza				X									Shrub legume
Lotus corniculatus	Birdsfoot trefoil		X		X						X	X		Can root to depth of 1 m or more (Bennett et al. 1978)
Medicago sativa	Alfalfa		X		X						X	X		Grows in summer as well as spring and fall (Vogel 1981)
Melilotus alba	White sweet clover		X		X						X			Biennial
Melilotus officinalis	Yellow sweet clover		X		X						X			Biennial
Trifolium ambiguim	Kura clover		X	X	X	X							X	
Trifolium medium	Zigzag clover		X	X		X	X							
Trifolium pratense	Red clover		X	X	X						X			Requires adequate moisture (Vogel 1981)
Trifolium repens	White clover		X	X	X						X	X		Inadequate winter cover (Vogel 1981)
Vicia spp.	True vetches			X				X		X				Annuals and perennials

[a]Rate of establishment.

1978). Yellow and white sweet clover (*Melilotus officinalis* and *M. alba*) may, on suitable soils, suppress slower-growing perennial species and continue to do so by reseeding (Vogel 1981). Alfalfa (*Medicago sativa*); white, crimson, red, kura, and zigzag clover (*Trifolium repens*, *T. incarnatum*, *T. pratense*, *T. ambiguum*, *T. medium*); and birdsfoot trefoil (*Lotus corniculatus*) have also been used for revegetation of spoils (Bennett et al. 1978). Alfalfa has a deeply penetrating taproot system; birdsfoot trefoil has a well-developed taproot system and will root to a depth of more than 1 m under good soil conditions; red clover has a deep taproot system; and kura clover is drought resistant, implying deep rooting (Bennett et al. 1978). Zigzag clover has a rhizomatous root system [Kawnacka (1961) as cited in Bennett et al. (1978)]. Flat pea (*Lathyrus sylvestris*), an introduced warm-season perennial, may eventually establish complete ground cover and successfully suppress associated vegetation and prevent establishment of invading plants (Vogel 1981). The flat pea cultivar Lathco has an extensive, deep taproot system, which makes it drought resistant (Bennett et al. 1978).

True vetches (*Vicia* sp.) are common invaders along roadways in the southern United States. Their matting type of growth helps protect the soil from erosion (Bennett et al. 1978). Crownvetch (*Coronilla varia*) is a perennial semicreeping rhizomatous legume, which is especially useful for areas that cannot be mowed. Growing to a height of about 0.8 m (Springer et al. 1969), it is recommended as a continuous, maintenance-free, erosion-control cover (Vogel 1981; Springer et al. 1969; Wright et al. 1978; Miles et al. 1973); Chemung and Penngift are superior cultivars for the Appalachian region (Vogel 1981). Wright et al. (1978) report that crownvetch persisted for two decades on roadsides without any maintenance. Penngift crownvetch escaped cultivation in Pennsylvania in the 1930s and had covered 4 ha when discovered (Atkinson 1970). Crownvetch can be established by inoculated seed or by setting individual plants 0.9 m apart or closer in winter. When crownvetch plants are interplanted in existing vegetation, no mulch or companion plants are needed; however, when seeded on bare ground, tall fescue (Springer et al. 1969), weeping lovegrass, or perennial rye (Vogel 1981) are recommended to provide cover the first year or two. Mowing is necessary only to control invaders when a continuous vegetational cover has not yet been established and should be no lower than 30.5 cm. Extracts from crown vetch foliage may inhibit the growth of germinated red oak seeds (Vogel and Curtis 1978).

Sericea lespedeza (Lespedeza cuneata) has been observed to persist as maintenance-free vegetation for two decades on various subsoils on roadsides (Wright et al. 1978). Vogel (1981) mentions aesthetics as a favorable point for its use and considers interstate, caricea, and the low-growing form Appalow superior cultivars. Sericea is a deep-rooted summer legume that dies back to the ground each winter (Menhinick 1967; Bennett et al. 1978). Sericea can be planted as seed-bearing stems in mulch in the fall, or as scarified seed in the spring, together with seed of annual lespedezas, weeping lovegrass, tall fescue, or bermuda grass, to provide first-year cover (Springer et al. 1969; Vogel 1981).

Lespedeza bicolor and the closely related *Lespedeza japonica* and *Lespedeza thunbergii* (Springer et al. 1969) are introduced shrub legumes, 1.2 to 3 m tall when mature, with heavy underground root systems (Springer et al. 1969). They are intolerant to shade (Vogel 1981). Species other than legumes that have been recommended for revegetation of disturbed areas are listed in Table 8.

Table 8. Nonleguminous species recommended for revegetation of disturbed areas

Genus and species	Common name
Amorpha fruticosa	Indigo bush
Cornus amomum	Silky dogwood
Cornus stolonifera	Red-osier dogwood
Crataegus sp.	Hawthorn
Elaegnus umbellata	Autumn olive
Ligustrum amurense	Amur privet
Lonicera japonica	Japanese honeysuckle
Lonicera maackii	Amur honeysuckle
Lonicera morrowii	Morrow honeysuckle
Lonicera tatarica	Tartarian honeysuckle
Prunus besseyi	Western sand cherry
Prunus virginiana	Choke cherry
Pueraria lobata	Kudzu
Rhus aromatica	Fragrant sumac
Rhus copallina	Shining sumac
Rhus glabra	Smooth sumac
Robinia fertilis	Bristly locust
Sambucus canadensis	American elder

Kudzu (*Pueraria lobata*) seedlings or crowns should be planted in well-prepared holes, away from plant competition, 1.8 m apart, in rows that are 3 m apart. Annual mowing, hand-cutting of runners, or use of herbicides will control growth of the vines in unwanted areas, and 0-20-20 fertilizer should be applied until adequate cover is established (Springer et al. 1969). Witkamp et al. (1966) planted kudzu in 60-cm-deep holes, 1.4 m apart at Copperhill, Tennessee. Five years later the plants had spread about 30 m from the original holes. The foliage covered the soil completely 10 m from the original planting, and roots extended 10 cm into the soil. Kudzu stems have been reported to have grown 20 to 25 m in length in one growing season (Bennett et al. 1978).

To establish Japanese honeysuckle (*Lonicera japonica*), plants should be transplanted when soil is moist in holes prepared with 10-10-10 fertilizer. Mowing and fertilization are not necessary after establishment (Springer et al. 1969). Japanese honeysuckle retains green foliage during winter (Vogel 1981), which positively influences its water uptake because of evapotranspiration during the nongrowing season. Atkinson (1970) recommends Japanese honeysuckle for waste areas. Handley (1945) strongly recommends it for a wildlife food source and warns of its ability to choke out all other low-growing vegetation. When neglected, however, honeysuckle stands can become a suitable habitat for various kinds of weed trees (Foley 1972). Japanese honeysuckle is difficult to eradicate due to its extensive, well-developed root system (Leatherman 1955). It typically roots to a depth of 15 to 30 cm in moist soil, attaining depths of 1 m in drier soils. In stony, clay fill soil without definite profile, root penetration of 17-month-old honeysuckle ranged from 15 to 50 cm (Leatherman 1955).

Amur, Morrow, and tartarian honeysuckle (Lonicera maackii, L. morrowii, and L. tatarica), introduced shrubs, must be planted as seedlings or root cuttings because direct seeding has been unsuccessful. They initiate early growth in the spring (Vogel 1981).

Fragrant and shining sumac (Rhus aromatica and R. copallina) should be planted as seedlings or root cuttings 1.2 to 1.5 apart. Reports on rooting depths of sumac species vary. Smooth sumac (R. glabra), an invading species in upland prairie, has been reported to have shallow, spreading roots (Auerbach et al. 1959). Weaver and Kramer (1932), however, considered it a deep-rooting species.

Bristly locust (Robinia fertilis) or the cultivar Arnot can be planted as seedlings or as scarified seed with a special inoculum. The plant spreads from root suckers and often forms dense thickets. Root suckers of this kind, however, either are retarded in development or will not occur in well-sodded areas (Vogel 1981). Miles et al. (1973) mention Arnot bristly locust for beautification of sites.

Indigo bush (Amorpha fruticosa) is a good, native site conditioner for the invasion of other native species (Vogel 1981).

Autumn olive (Elaeagnus umbellata), an introduced species whose initial survival and growth are usually good when planted in established cover of herbaceous vegetation (Vogel 1981, Wyman 1969), has been suggested as a nurse plant for crop trees (Vogel 1981).

Remaining shrub species (as listed by Vogel for Tennessee) are redosier dogwood and silky dogwood (Cornus stolonifera and C. amomum), hawthorn (Crataegus sp.), amur privet (Ligustrum amurense), western sand cherry and choke cherry (Prunus besseyi and P. virginiana), and American elder (Sambucus canadensis). Information on rooting depth of these shrubs is not available, except for Sambucus, which is reported to be deep rooting.

Of the species discussed for revegetation purposes, Lespedeza cuneata, L. stipulacea, L. striata, Lonicera japonica, and Prunus sp. have been found in Roane County, Tennessee, in disturbed habitats (Mann and Bierner 1975). Andropogon gerardi, Festuca elatoir, Crataegus boyntoni, C. disperma, Lespedeza cuneata, Lonicera japonica, Rhus radicans, Rosa setigera, Cornus amomum, and Sambucus canadensis occur naturally in Roane County, Tennessee, in wet habitats. Andropogon gerardi, A. virginicus, Festuca elatior, Crataegus boyntoni, C. crusgalli, Lespedeza cuneata, Lonicera japonica, Prunus sp., Rhus copallina, R. glabra, R. radicans, Rosa setigera, and Sambucus canadensis occur in field habitats. Andropogon gerardi, A. scoparius, A. virginicus, Crataegus crus-galli, Rhus aromatica, R. copallina, R. glabra, Rosa carolina, Rosa setigera, and Lespedeza sp. occur naturally in dry-field habitats in Roane County, Tennessee (Mann and Bierner 1975).

Naturally invading species in old fields occurring in Roane County, Tennessee, include Lonicera japonica, Campsis radicans, Rubus sp., Vitis conerea, Parthenocissus quinquefolia, Juniperus virginiana, Pinus echinata, P. virginiana, Sassafras albidum, Prunus serotina, Liquidambar styraciflua, and Diospyros virginiana (Mann and Bierner 1975).

Low-Maintenance Horticultural Species

Ornamental plants are generally slower in establishment and require more care in planting and maintaining. Species requiring less maintenance are listed in Table 9 together with summaries of available information.

Day-lilies (Hemerocallis sp.) do best in partial shade and respond well to water and fertilizer (Springer et al. 1969). Foley (1972) mentions their large root systems and ability to withstand drought, implying a deep-rooting habit. Plantain-lilies (Hosta sp.) grow in average garden soil, in sun or shade, and should be fertilized annually (Foley 1972). Lily-turf (Liriope spicata) and dwarf lily-turf (Ophiopogon japonicus) quickly form solid mats, with a dense sod like growth. They need division every few years and can be reset in the fall or spring and require no further special care (Foley 1972). They tolerate poor drainage and are somewhat drought tolerant (Duble and Kell 1977).

Hypericum species are well suited to sandy soils in full sun or light shade (Foley 1972, Wyman 1969). Hypericum calycinum (Rose of Sharon) is reported to do well on heavy clay, on chalky, and on dry soils in poor sites in sun or shade (Boddy 1974). It covers the ground effectively with foliage to a height of 30 cm and retains most of its leaves throughout a normal winter (Boddy 1974).

Everlasting pea (Lathyrus latifolius) is slow in providing cover. The soil must be well limed and fertilized and seeds need an inoculum (Springer et al. 1969). This pea is recommended by Wright et al. (1978) as promising for the southeastern United States. Like other Lathyrus

Table 9. Low-maintenance horticultural species

Genus and species	*Common name*	Drought resistant	Shallow rooted	Sun tolerant	Shade tolerant	Fast growing	Good cover	Comments
Herbaceous plants								
Aegopodium podograria	Goutweed			X	X			*First frost kills foliage (Foley 1972)*
Ajuga reptans	Bugleweed		X					Needs constant water supply (Duble and Kell 1977)
Dichondra repens	Dichondra		X					Needs frequent watering (Atkinson 1970)
Euonymus fortunei		X	X		X	X	X	
Hamerocallis spp.	Day-lilies	X						
Hosta spp.	Plantain lilies			X	X			Annual fertilization (Foley 1972)
Hypericum calycinum	Rose of Sharon			X			X	Retains foliage throughout winter (Boddy 1974)
Lathyrus latifolius	Everlasting pea	X						Deep taproot
Liriope spicata	Lily-turf	X				X	X	
Lippia canescens	Frog-fruit					X		
Ophiopogon japonicus	Dwarf lily-turf	X				X	X	
Polygonum affini	Border jewel						X	
Polygonum bistorta	Snakeweed						X	
Polygonum cuspidatum	Japanese fleeceflower							Dies back in fall (Vogel 1981)
Polygonum reynoutria	Dwarf fleeceflower			X		X	X	
Sasa pumila	Dwarf bamboo					X	X	
Sasa variegata	Dwarf bamboo					X	X	

Table 9. (continued)

Genus and species	Common name	Drought resistant	Shallow rooted	Sun tolerant	Shade tolerant	Fast growing	Good cover	Comments
Herbaceous plants (continued)								
Sasa veitchi	Dwarf bamboo					X	X	
Vinca minor	Periwinkle				X		X	
Xanthorhiza simplissima	Yellowroot					X	X	
Vines								
Akebia quinata		X		X	X			
Lycium chinense	Matrimony vine							
Menispermum canadense	Moonseed						X	
Shrubs								
Andromeda polifolia	Bog rosemary							Acid soil
Berberis spp.	Barberries	X						
Calluna spp.	Heather		X					
Ceanothus spp.	Redroot						X	Evergreen
Chaenomeles spp.	Quince						X	Dense shrub; requires occasional pruning (Wyman 1969)
Cotoneaster spp.	Cotoneaster	X		X		X	X	Evergreen or deciduous shrubs susceptible to fir blight and red spider (Wyman 1969)
Erica spp.	Heath		X					
Forsythia suspenza	Forsythia		X					Aesthetically pleasing tall-growing cover (Foley 1972)
Gaultheria spp.	Wintergreen				X			

Table 9. (continued)

Genus and species	Common name	Drought resistant	Shallow rooted	Sun tolerant	Shade tolerant	Fast growing	Good cover	Comments
Shrubs (continued)								
Gaylussacia brachycera	Box huckleberry			X				Slow growing
Jasminium nudiflorum	Jasmine		X					Tall-growing cover (Foley 1972)
Juniperus horizontalis	Creeping juniper	X	X					Slow growing, susceptible to twig blight and insect pests (Wyman 1969)
Kalmia latifolia	Mountain laurel							Acid soil
Leiophyllum buxifolium	Sand myrtle							Acid soil
Lonicera pileata	Honeysuckle						X	Semievergreen foliage
Pachystima canbyi	Cliff-green							Excellent shrub cover under trees (Atkinson 1970)
Potentilla spp.	Potentilla			X			X	Excellent deciduous, spreading shrubs (Boddy 1974)
Rhus aromatica	Fragrant sumac							Does well in poor soil
Rosa nitida	Rose		X				X	Rapid growth with fertilization (Springer et al. 1969), forms low thicket
Spiraea spp.	Spiraea					X		Fibrous root system
Symphoricarpos orbiculatus	Coralberry							Spreads easily
Vaccinium corymbosum	Tall blueberry							Acid soil
Vaccinium vitis-idaea	Mountain cranberry			X				Acid soil
Veronica spp.	Hebes						X	Evergreen shrub; dry, sandy soil (Wyman 1969)

sp., it has a deep taproot. Other legumes mentioned for ground cover are brooms (*Cytisus* sp. and *Genista* sp.). According to Foley (1972), they do best in dry, poor soil; however, Boddy (1974) considers them suitable for heavy clay soils.

Japanese fleeceflower (*Polygonum cuspidatum*) is mentioned by Vogel (1981) for its aesthetic qualities, but its stems die to the ground in the fall. It does not readily spread by seed into stands of established vegetation. Dwarf fleeceflower is used commercially as an ornamental ground cover (Vogel 1981). Atkinson (1970) mentions *P. cuspidatum* var. *compactum* (sold as *P. reynoutria*) as useful on sunny dry banks and problem areas where there is good drainage. Foley (1972) mentions *P. reynoutria* as thriving in locations where other plants are not satisfactory in sun or shade. Other *Polygonum* species recommended for ground cover are *P. affini* (border jewel) and *P. bistorta* (snake weed) (Atkinson 1970).

Other herbaceous horticultural species to be considered are goutweed, yellow root, and *Lippia* and *Sasa* species. *Aegopodium podograria* (goutweed) grows anywhere it can take root in sun or shade, although the first frost kills the foliage (Foley 1972). Atkinson (1970) considers it a very offensive plant because of its persistent spread and lists it under perennial weeds with penetrating roots. *Xanthorhiza simplissima* (yellow root) increases rapidly by underground stolons, forming dense mats of foliage throughout the spring and summer (Wyman 1956). It needs a moist habitat according to Foley (1972). It occurs in Roane County, Tennessee, in wet habitats (Mann and Bierner 1975). Drought-resistant *Lippia canescens* is a fast-growing perennial, which spreads by underground stems that root as they grow. Sod transplants should be set as close as possible for an immediate effect (Foley 1972). Sasa pumila, S. variegata, and S. veitchi (bamboo) are listed by Wyman (1956) as rapidly growing and functioning ground covers.

Vinca minor, a popular ground cover, requires partial shade, as does Hedera sp., Pachysandra sp., and Ajuga reptans. Foley (1972) reports that Ajuga reptans has a shallow root system. It can withstand sun (Wyman 1956); however, it requires a constant water supply, particularly in hot weather (Duble and Kell 1977). Dichondra repens requires sandy soil and frequent watering according to Atkinson (1970). It tolerates heavy clay, needs a regular supply of moisture due to shallow rooting, and requires regular feeding (Duble and Kell 1977). Euonymus fortunei roots deeply and is used for lawn in shade. It is susceptible to scale and needs spraying with diazinon (Atkinson 1970). Boddy (1974) considers it not exceptionally rapid in spreading, excellent in shade, good in sun, and best planted about 60 cm apart to obtain reasonably quick coverage. It is capable of forming a solid 40 cm-high mat of trailing stems and may be propagated with pieces of root stem.

Vines that are considered to require low maintenance include moonseed (Menispermum canadense), which is a vigorous perennial for poor soils, but may be a pest when planted in the wrong places (Foley 1972). Matrimony vine (Lycium chinense) is a good soil binder, suckering as it spreads. Its stems are thorny and it is hardy and easy to grow (Foley 1972). Akebia quinata is suited for sun or partial shade. It grows 1 to 5 m each year, requires well-drained soil, is drought resistant, and has deep-growing roots (Dimond and MacCaskey 1977).

Rose species (*Rosa* sp.) are rather slow growing, but heavy fertilization can result in rapid growth (Springer et al. 1969). According to Foley (1972), rose species require no special soil, but the usual care given any shrub gets it off to a good start. *Rosa nitida* is suggested by Boddy (1974) as most suitable for ground cover and banks and is capable of forming a low thicket when planted 60 to 90 cm apart. Cotoneasters (*Cotoneaster* sp.), closely related to *Crataegus* species (Wyman 1969), are deep rooted according to Duble and Kell (1977) and Foley (1972). They are evergreen or deciduous shrubs that do well in hot, dry situations on banks or slopes (Foley 1972). They are susceptible to infestations of fireblight and red spider (Wyman 1969). *Cotoneaster horizontalis* plants should be planted 1 m apart for quick cover establishment (Boddy 1974).

Peaty, sandy soil on slight slopes and good drainage are required for heath and heather species (*Erica* sp., *Calluna* sp., *Daboecia cantabrica*, and *Bruckenthalia spiculifolia*) (Foley 1972). Members of the heath family require acid soils for good growth (Wyman 1956). *Erica* sp. and *Calluna* sp. have shallow roots according to Atkinson (1970). *Gaultheria* sp. needs mulch and shade or partial sunlight (Foley 1972, Boddy 1974, Bonnie and Thompson 1975). Box huckleberry (*Gaylussacia brachycera*) is slow growing and can be grown in full sun in well-prepared acid soils (Foley 1972). Atkinson (1970) reports *Gaylussacia peregrina* grows well in semishade on moist sandstone or clay soil.

Pachystima canbyi, native to the mountains of Virginia and the Carolinas, forms a ground cover beneath rhododendrons and azaleas (Foley 1972). *Pachystima*, a 30-cm-high, hardy shrub, forms an excellent cover under trees (Atkinson 1970). *Vaccinium vitis-idaea* grows in full sun in moist acid soil and may be propagated by root division (Foley 1972). *Vaccinium corymbosum*, a vigorous bush, will grow 15 to 30 cm high if the soil is right (Wyman 1969). *Kalmia* sp. requires acid soil and moisture (Wyman 1969). Sand myrtle (*Leiophyllum buxifolium*) is a 15- to 20-cm bush requiring acid soil and grows in any exposure (Atkinson 1970). Bog rosemary (*Andromeda polifolia*) needs acid soil rich in humus (Foley 1972).

Hebes (*Veronica* sp.) are bushy evergreen flowering shrubs with good ground-covering capacity (38 cm high, 30 cm wide). When cut back in spring, they are induced to produce vigorous new growth from the base (Boddy 1974). Hebes do best in dry, mostly sandy soil (Wyman 1969).

Shrubby, deciduous potentillas are excellent spreading bushes requiring little attention (Boddy 1974). *Potentilla fruticosa* will grow in areas where nothing else will and does well in full sun (Atkinson 1970).

Evergreen, nonconiferous California natives, *Ceanothus* spp. are used on freeway embankments in California, and some are hardy for Tennessee. Ground-cover varieties used are *C. gloriosus*, *C. maratimus*, *C. griseus*, and *C. protratus* (Atkinson 1970). *Ceanothus ovatus* is found in Tennessee but is not a ground-cover species as such.

Most barberries (Berberis sp.) are very drought tolerant (Dimond and MacCaskey 1977). They serve as an alternate host for black stem rust for wheat (Wyman 1969). Quinces (Chaenomeles sp.) grow as dense shrubs in any good soil, require occasional pruning, and are susceptible to San Jose scale (Wyman 1969).

Symphoricarpos orbiculatus (coralberry) is easy to grow in any soil (Foley 1972). It is a 1-m-high shrub that suckers readily and spreads easily (Wyman 1969; Boddy 1974).

Rhus aromatica requires no maintenance and will do well in poor soil. Pruning induces denser growth, and it can be propagated by division of the roots (Foley 1972).

Lonicera pileata is a low-growing bush honeysuckle, which spreads horizontally and has bright semievergreen foliage. When planted 1 m apart, the bush can soon form a complete canopy low over the ground (Boddy 1974). Lonicera prostrata is also recommended for ground cover (Wyman 1969).

Spiraeas have fibrous roots and are easily transplanted. Spiraea x billiardi increases by underground stems, forms dense mats, and may grow 1.8 m tall. Spiraea cantoniensis is considered the best spiraea for the south. Spiraea vanhouttei is a vigorous grower and will grow 1.8 m tall (Wyman 1969). Spiraea douglassi occurs in field habitats in Roane County, Tennessee (Mann and Bierner 1975).

Miles et al. (1973) list Forsythia for beautification. Foley (1972) regards Forsythia suspenza and Jasminium nudiflorum as tall-growing ground cover. Forsythia spp. require little or no care, are not susceptible to insect pests, require only ordinary soil (Foley

1972), and are aesthetically pleasing. Wyman (1956) suggests that forsythias should be planted 2.5 to 3 m apart to give the plant plenty of room to expand fully at maturity. They will generally form a dense cover.

Spreading prostrate junipers (*Juniperus horizontalis*) are considered by Boddy (1974) to be superb ground cover over large areas. They are drought tolerant (Duble and Kell 1977). They should be planted 1 to 1.8 m apart. They average a lateral growth rate of 15 cm a year and root while spreading, but they are not considered rampant ground covers (Boddy 1974). Atkinson (1970) lists them under carefree ground covers. Junipers are reported to be susceptible to twig blight (phomopsis) and insect pests (Wyman 1969).

ECOLOGICAL POTENTIAL OF PLANT SPECIES

Plant-water relations and rooting-depth potential are important factors to consider in determining plant species potentially suitable for establishment on low-level solid nuclear waste disposal sites.

WATER DEMAND OF PLANT SPECIES AND WATER YIELD IN WATERSHEDS

Important aspects of plant-water relations to consider include water requirements of plant species, water-use efficiency, evapotranspiration differences among plant species, rooting depth of plant species in relation to water use, and water yield from a watershed as a result of vegetational cover, retention, and exchange.

Briggs and Shantz (1914) show a wide range of water requirements (the amount of water transpired in the production of a unit of dry matter) to produce a given weight of dry matter in crops and native plants of the Great Plains. For example, western wheatgrass (*Agropyron smithii*) requires more than 2 times as much water as buffalo grass (*Buchloe dactyloides*) for each kilogram of dry matter produced; bromegrass (*Bromus inermis*) requires more than 2.5 times as much water as sugarbeet (*Beta vulgaris*); and flax (*Linum usitatissimum*) requires more than 3 times as much water as millet (*Setaria* sp.). Often, different varieties of the same crop differ widely in their water requirements; for example, the variety of alfalfa (*Medicago sativa*) having the highest water requirements needs 1.5 times as much water as the variety having the lowest water requirements (Briggs and Shantz 1914). Briggs and Shantz (1914) observed that the crops with relatively low water requirements were late-maturing crops that grew best during the hottest and driest portion of the season. De Wit (1958, as cited in Van Keulen 1981) determined that when nutrient levels are not too low, the expected relationship between water required by crop plants and dry matter produced depends on the irradiance.

Weaver (1941) studied water use (i.e., the quantity of water used by plants in producing a unit of dry matter, exclusive of roots, plus the amount lost by evaporation from the surface of the soil occupied by the plants during their period of growth) of prairie grasses. The highest water usages in the prairie were those of western wheatgrass (*Agropyron smithii*), using 1465 kg, and bluegrass (*Poa pratensis*), using 703 kg. The lowest was that of big bluestem (*Andropogon gerardi*), using 381 kg. Side-oats grama (*Bouteloua curtipendula*), blue grama (*Bouteloua gracilis*), and little bluestem (*Andropogon scoparius*) were intermediate, using 538, 488, and 461 kg, respectively. Water usage varied over the season. When the prairie plots were clipped, water usage increased for blue-grass (21% more) and blue grama (4% more) and decreased for big blue-stem (3% less), little bluestem (30% less), and wheatgrass (31% less). Yields of clipped compared to unclipped grass were 91% for side-oats grama, 88% for wheatgrass, 85% for blue grama and little bluestem, 73% for bluegrass, and only 57% for big bluestem.

Water consumption of vegetation stands in various climatic regions is discussed by Larcher (1980). Under similar climatic conditions, forests transpire appreciably more than grasslands, and grasslands in turn transpire more than heath. The greatest water turnover is always found in stands of plants growing in wetlands (Larcher 1980).

Water-use efficiency (the ratio of dry matter produced to the amount of water used) has been determined to be greatest when deeper rooting has been established (Burton et al. 1957; Doss et al. 1960, 1962). When, before irrigation, 85% soil moisture has been lost (compared to field capacity) versus 65 or 30% grasses and sericea lespedeza develop deeper roots, which results in more efficient water use when irrigated (Doss et al. 1960, 1962). For common bermuda grass (Cynodon dactylon), rooting depth averaged 203 and 132 cm when 85 and 30% soil moisture had been lost and when water-use efficiency was 3.9 compared to 2.4, respectively. For sericea lespedeza (Lespedeza cuneata), rooting depth was 130 cm and 99 cm when 85 and 30% soil moisture had been lost and when water-use efficiency was 2.8 compared to 1.5, respectively (Teare 1977). Wright and Dobrenz (1970) found in blue panic grass (Panicum antidotale), the highest efficiency of water-use when the largest root biomass was present while water stress had a negative influence on the efficiency of water use. Dobrenz et al. (1969a,b) found clonal differences in blue panic grass to be related to water use efficiency. They found that drought-tolerant clone seedlings had fewer stomata per unit leaf area than drought-susceptible clones. The two clones with the highest and lowest mean stomata density did not differ significantly in the amount of water transpired. The clone most efficient in water use was one of the two clones with the most stomata. This clone transpired essentially the same amount of water as the least efficient clone, but the most efficient water user produced 1.5 times the dry forage of the least efficient one (Dobrenz et al. 1969a).

Water loss by transpiration may occur from any plant part exposed to the atmosphere. However, it occurs principally from leaves and almost entirely through stomatal pores (Noggle and Fritz 1976). Cuticular transpiration is simply the evaporation of water from wet epidermal cells (Thomas et al. 1960). For young leaves with a thin cuticle and partly developed stomata, cuticular transpiration may exceed stomatal transpiration (Thomas et al. 1960). Stomatal control is considered by Teare (1977) to be, in part, genetically determined. Water loss is controlled chiefly by stomatal resistance in mature leaves and micrometeorological influences, particularly atmospheric demand (Tranquillini 1963; Willis and Jefferies 1963; Ritchie 1971; Teare 1977; Luxmoore et al. 1981). The water vapor gradient necessary for evapotranspiration is mostly influenced by net radiation (Briggs and Shantz 1914; Ritchie 1971; Teare 1977). When soil water becomes limiting in the root zone, the soil water potential becomes a dominating factor influencing evaporation rates (Ritchie 1971). Willis and

Jefferies (1963) review how different plant species close their stomata at different water-deficit levels. Plants of dry dunes close their stomata sooner than some shade plants. Sojka and Stolzy (1980) found evidence that low oxygen diffusion rates in soils during periods of excess soil water bring about stomatal closure, reducing evapotranspiration in a wide range of species like tomato, jojoba, cotton, and wheat. Teare et al. (1973, as cited in Teare 1977) reported differences between soybean (Glycine max) and sorghum (Sorghum bicolor) evapotranspiration rates. Soybean stomata did not close as stomatal resistance increased in response to high atmospheric demand. Soybeans require a uniform supply of water and have one-half the root biomass of sorghum. Sorghum is considered a drought-resistant species and reduces its evapotranspiration rate through stomatal closure as stomatal resistance increases (Teare 1977).

Instead of measuring evaporative flux in or above vegetation canopies, some investigators calculate evapotranspiration of vegetation from measurements of various soil-water characteristics (Slatyer 1967; Kramer 1969). LaRue et al. (1968) point out that estimates of evapotranspiration based on samples of soil-water characteristics are prone to error unless large numbers of samples are taken to the maximum rooting depth of the plants.

Luxmoore et al. (1977) studied the water balance of two prairie sites (Andropogon gerardi, Sorghastrum nutans) and an oak-hickory forest site (Quercus alba, Carya sp.) at the University of Wisconsin Arboretum, Madison. Field water balance data were measured at 30-cm intervals to a depth of 180 cm, and evapotranspiration was calculated from those data. The average evapotranspiration rates thus calculated were similar for the prairie and the oak-hickory sites. In comparing his data with those from a study of Sartz (1972) on evapotranspiration from oak-hickory vegetation in southwestern Wisconsin, Luxmoore et al. (1977) reported that the comparison suggested that an additional 26% of the water transpired by hardwood forests may be attributed to deep roots and that water stress may have been indicated for the oak-hickory vegetation for 24 d out of the 16-week growing season.

McColl (1977) observed no clear differences between values of the drying-rate constant of soils of clear-cut fields and adjacent eucalyptus-forested fields to depths of 76 cm. McColl suggests that this is due to the roots in the forested area drawing water from deeper soil layers.

Gaertner (1963), in a review article on water relations of forest trees, points to Shear and Stewart's (1934) findings that tree species (white pine excepted) remove water from soil most rapidly when new foliage is produced. White oak and white pine removed more water from the first 1.2 m of soil than green ash (Fraxinus pennsylvanica) and silver maple (Acer saccharinum). Soil moisture was affected to a depth of 3.5 m under white oak, 3 m under larch, 2.5 m under maple and white pine, and 2 m under green ash.

Tew (1969) makes the point that below 1 m of surface soil no significant increase of water yield can be expected when grasses replace deeply rooted trees and shrubs. When tall oatgrass (Arrhenatherum elatius), smooth brome (Bromus inermis), timothy (Phleum pratense), and orchard grass (Dactylis glomarata) were well established on the sites tested, soil was dried completely to a depth of at least 1 m. When there was no vegetation on the sites, available soil moisture remained near field capacity at depths below 0.3 m.

Gardner and Woolhiser (1978) suggest that the total runoff in a watershed will be less if the area is covered with a deep-rooted evergreen than with shallow-rooted deciduous species.

Hewlett and Hilbert (1961, as cited in Krámer 1969) found over threefold increases in streamflow from a watershed during the first year after conversion of a mature forest to low-growing vegetation in southwestern North Carolina (Coweeta Hydrologic Laboratory).

Rowe and Reimann (1961) compared soil moisture in plots in a watershed in southern California. The plots either were covered by brush vegetation or had been mechanically converted to grass vegetation. Data indicated a greater amount of evapotranspiration from the brush soils than from the grass-covered soils. They attributed this to the following circumstances: (1) the brush continued use of water over a longer period of time and (2) the brush used more water from the deeper 0.7 to 3.7-m soil depths. During a year of low rainfall, vegetation cover did not affect percolation through the soil, because the rainfall was not in excess of that required to wet through the root zone and satisfy increased evapotranspiration losses. When forb growth was uncontrolled and residual 2,4,5-T in the soil most likely acted as a growth-promoting substance, the grass-forb cover dried the soil below field capacity throughout a full 3.7-m depth and to or below wilting point down to 1.8 m. Rowe and Reimann (1961) concluded that there are no differences in water balance in the surface 1 m of soil under brush, forb, or grass vegetation. Conversion from brush to grass on shallow soils will more likely decrease water yield from under the vegetation due to higher evapotranspiration from the grass during the rainy season (Rowe and Reimann 1961).

Kelly (1968) found water losses in soils vegetated either with *Festuca elatior* var. *arundinacea* or with *Andropogon virginicus* to be recharged rapidly by rainfall in fields of Roane County, Tennessee.

Water yield in a watershed represents the amount of rainfall that percolates through the soil and is not taken up by the roots (Rowe and Reimann 1961), or the difference between water input (precipitation), output (interception, evaporation, transpiration, soil evaporation, drainage, runoff), and storage (interception, soil water) (Luxmoore et al. 1981). When roots fully occupy a soil and atmospheric conditions are favorable, plants may dry out the root-occupied soil to a water tension of 1.5 MPa (15 bar), generally the permanent wilting point (Colman 1953; Kramer 1949; Bennett and Doss 1960; Teare 1977). Since rainfall averages 132 cm annually in the area of the waste disposal sites at Oak Ridge, different vegetation types will not significantly influence the water balance if only shallow-rooting vegetation is allowed on the sites.

One successful attempt to change the water table and cause a saline seepage area to dry out has been reported from northern Great Plains small-grain dryland farms (Halverson and Reule 1980). Alfalfa (*Medicago sativa*) grown in an area where total precipitation averaged 91 cm year reduced or prevented deep percolation of soil water below the root zone by evapotranspiring as much or more soil water than was usually received from precipitation during the growing season. Alfalfa was successful in the seepage area when occupying 80% of the recharge area, because it could extract water from deeper depths than could small-grain crops such as oats (*Avena sativa*) and wheat (*Triticum aestivum*) or such native range grasses as tall wheatgrass (*Agropyron elongatum*) and alta tall fescue (*Festuca arundinacea*) (Halverson and Reule 1980).

ROOT GROWTH

Factors influencing rooting depth of plant species include genetics, seasonality, drought, root and aboveground biomass, fertilization, and properties of the soil (pH, organic matter, oxygen and aeration, moisture, and structure).

Rooting Depth and Genetics

Troughton and Whittington (1969) mention three ways of analyzing genetic variation in root systems: (1) by a study of excised root systems, (2) by a study of the effects of grafting on the growth of the composite plant, and (3) by a study of the growth of whole plants with different types of root systems in various environments. They cite a number of references giving experimental evidence that genetically determined variation exists in root systems.

One example of genetic variation in root systems is given by Carrigan and Frey (1980). Root volumes were measured at regular intervals during the growth cycle of cultivated and weedy oat species grown hydroponically. Final root volumes differed significantly over time as did the pattern of increase in root volume. One oat variety had a final root volume 3 times larger than that of the others. Root-to-shoot ratios varied from 0.03 to 0.09.

Distribution of the roots in the soil is one of the more important aspects of the question of whether species can be said to be shallow or deep rooted. Sutton (1969), discussing the structure of root systems of conifers, claims that "species and even genera have been credited with characteristic root forms" and considers descriptions such as "the shallow-rooted spruce" and "the deep-rooted pine" as dangerous and unwarranted generalizations. Troughton and Whittington (1969) give an example, from Weaver and Clements' (1938) description of prairie grasses, of environmental influences overriding possible genetic differences in grass species with regard to rooting depth. Roots in tall-grass prairies fall into three, more or less distinct, absorbing layers. In short-grass prairies where the soil is seldom moist below 61 cm (Weaver 1926), only the top 36 to 61 cm of soil induce profusely branched roots. The roots of short-grass prairie species penetrated more deeply in mixed prairie than in the short-grass prairie, whereas the root systems of the tall-grass prairie species were abbreviated in depth.

Although there are hereditary characteristics controlling root growth of different plant species, character modification is usually an indicator of soil conditions (Weaver 1926). Hermann (1977) considers initial development of roots to be largely under genetic control, while environmental factors appear to have a stronger influence on later development of root characteristics.

Habitat, Rooting Depth, and Root Activity

Weaver (1958) reviewed marked differences in root habit of various grasses in different habitats. Western wheatgrass averages a rooting depth of 2 to 2.5 m in zonal prairie soil or chernozem, 3 m in loess hills, only 79 cm in a silty clay-loam having a very compact clay pan at 10- to 104-cm depth, and 97 cm in a well-drained clayey subsoil overlying unweathered limestone. Roots of Kentucky bluegrass were restricted in one soil type to the upper 18 cm and were 82% of total weight, whereas in another soil roots weighed 3 to 5 times more and penetrated as deep as 51 cm. The tested soils were similar in pore space throughout, but in the former soil the soluble phosphorus and exchangeable potassium were extremely low (Weaver 1958). Weaver (1926) reports that in light sandy soil in eastern Nebraska, Kentucky bluegrass roots completely filled the soil to a depth of 0.8 m. They were numerous to the 1.5-m level, and a few reached a depth of 2.1 m.

Sprague (1933) differentiates root behavior of grasses on podzolic soils of the eastern half of the United States from those on prairie chernozem soils, as studied extensively by Weaver and his colleagues, even though the species of plant remains the same. Sprague (1933) found 50% of the root system of Kentucky bluegrass in the first 2.5 cm (1 in.) of soil with less than 1% occurring below 25 cm. Peterson et al. (1979) found bluegrass rooting to a depth of 51 cm in loess soils with uniform physical characteristics to a depth of 127 cm.

O'Donnell and Love (1970) point out that the importance of roots in the top 20 to 25 cm of soil is easily overestimated and the roots below this depth underestimated. By means of ^{32}P-tagged injections in the soil, O'Donnell and Love found significant root activity to a depth of 76 cm in Kentucky bluegrass.

Harris et al. (1977) found 80 to 90% of the lateral root biomass of the Liriodendron forest in Walker Branch Watershed, Tennessee, in the upper 30 cm of the soil, but they point out that although not more than 5% of the belowground biomass will be deeper than 60 to 70 cm, this fraction might be physiologically important in water metabolism and nutrient cycling.

Rooting Depth and Seasonality

Sprague (1933) observed that root growth of different grasses differed over the growing season, that the roots differed in appearance over the growing season, and that they occupied different soil depths at progressively different times of the year. Kentucky bluegrass and colonial bentgrass passed through identical physiological cycles of growth, but growth response to increased spring temperature was initiated earlier for bluegrass than for bentgrass (Sprague 1933). In tall-grass prairie, the greatest root increment has been found to occur early in the growing season in the A1 horizon of the soil, while in deeper horizons, maximum root growth has been found to occur later in the growing season (Dahlman 1968b).

Rooting Depth and Drought Tolerance

Burton et al. (1957) reported that differences between various grasses in drought tolerance were largely a function of the ability of the grasses to send many roots into lower strata of soil. Blue-bunch wheatgrass (*Agropyron spicatum*), a perennial grass, in the northern intermountain region of the United States was outcompeted by cheatgrass (*Bromus tectorum*), an introduced winter annual, due to the latter's ability to grow roots deeply in the fall and winter after germination, thus gaining control of the site before the former initiated growth of roots in the spring (Harris 1967, 1977). *Bromus tectorum* placed a major stress on the soil moisture supply before the needs of *Agropyron spicatum* arose (Harris 1967).

Rooting Depth, Root Biomass, and Aboveground Biomass

Because roots are in competition with shoots for the carbohydrates needed for growth, mowing and grazing of herbaceous plants inhibit root formation as do pruning, crown cutting, defoliation, and shading (Lyr and Hoffmann 1967). Soil dryness, mineral salt deficiency (especially nitrogen), and higher soil temperatures increase the root-to-shoot ratio, whereas shading, nitrogen fertilization, higher air temperature, and sufficient soil moisture decrease the root-to-shoot ratio (Lyr and Hoffmann 1967). The first set of conditions seems to induce root growth because of the need for water and minerals under conditions still favorable (high soil temperature) for root growth, while the latter set of conditions indicates well-established vegetation with an active soil flora (nitrogen supply) and a protective organic layer over the soil for optimum soil moisture and suitable circumstances (air temperature) for good shoot growth.

O'Donnell and Love (1970) observed that Kentucky bluegrass, which in general is considered well adapted to mowing, had considerably higher total root activity when cut high than when cut low. The difference was twice as great early in the season compared to later in the season. They tested this with ^{32}P-tagged injections in the soil. Sprague (1933) found that Kentucky bluegrass root growth was not restricted by regular mowing to a height of 2 cm, but mowing of three bentgrass species, redtop, and hard fescue to this height reduced leaf area and the total quantity of food synthesized in the leaves so much that root growth was reduced. Hard fescue was the first grass to disappear from the plots. Wright (1962) clipped blue panic grass; the lower he clipped, the more root biomass and water-use efficiency was reduced. Doss et al. (1966) and Owensby et al. (1970) reported the same for bermuda grass and big bluestem, respectively.

Brouwer and De Wit's (1969) simulation model (ELCROS) suggests that for each given combination of species and environmental factors, there exists an optimum relationship between shoot size and root size, a so-called functional equilibrium. If one aspect of a plant is influenced, the equilibrium will be reestablished by compensatory action.

One set of data for comparing root biomass and total plant biomass is given by Ovington et al. (1963) from a study in central Minnesota. The average weights of roots and subterraneous stems in prairie, savannah, oakwood, and maize field sites were 4,824, 11,789, 14,977, and 650 kg/ha, which equal 91, 27, 8, and 1% of the total living plant biomass. For tall-grass prairie, 75% of the standing crop biomass may be belowground (Dahlman 1968b), which contrasts sharply with the less than 20% of total biomass found in the form of roots for woody ecosystems (Bray 1963; Dahlman 1968b). Kelly (1975) measured root biomass in a field dominated by broomsedge (Andropogon virginicus) and another dominated by fescue (Festuca elatior var. arundinacea) in Roane County, Tennessee, and found a 446- to 633-g/m^2 root biomass for broomsedge and a 278- to 794-g/m^2 root biomass for fescue. Estimated production rates for root biomass ranged from 0.55 to 1.31 g m^{-2} d^{-1} for the Andropogon community and 1.38 to 4.02 g m^{-2} d^{-1} for the Festuca community. Most of the seasonal change in root biomass occurred in the top 20 cm of the soil (Kelly 1975). Ninety-eight percent of the root biomass of the Andropogon community was in the top 30 cm of the soil compared to 85% for the Festuca community (Kelly 1975). Golley (1960) measured the standing crop of roots at a 15-cm soil depth of a Poa compressa-dominated field in Michigan and found that it changed from 1493 to 2516 g/m^2 from April to September.

Long (1959) observed that when fescue was seeded, it took several years for deep root establishment in Tennessee soils. After 4 years, 53% of the root biomass was in the upper 15 cm of the soil; after 6 years, 25% of the root biomass was in the upper 15 cm of soil.

Root Development, Fertilization, and pH

Root development in poor soils is comparatively more extensive than in rich ones, while at the same time a high concentration of fine roots can be found in nutrient-rich zones of the soil (Lyr and Hoffmann 1967; Teare 1977). An example of this is Buchholz and Neumann's (1964) finding (as cited in Lyr and Hoffmann 1967) that superficial rooting in a 56-year-old pine stand had doubled 2 years after nitrogen fertilization, while at the same time deep rooting had decreased. Of the fertilizer elements nitrogen is the most dependent on the moisture supply in the soil (Bolton 1981). The speed of downward movement of applied fertilizer will determine the location of nutrient-rich zones in the soil, which in turn will determine root proliferation. Van Keulen (1981) states that management practices that ensure the existence of a nonlimiting nitrogen supply throughout a plant's life enhance the efficiency of water use, while in situations where the total moisture supply is limited, application of nitrogenous fertilizer may lead to excessive vegetative growth and early use of the available moisture. Olson et al. (1964) note that the timing of nitrogen application is related to efficiency of water utilization. Burton et al. (1957) observed that nitrogen addition to soil decreased the quantity of water required to produce a kilogram of dry matter in experiments with grasses. Grasses, in their particular experimental circumstances, needed most of their root systems to supply sufficient water for optimum growth, but as little as 20% of the root system sufficed to supply most of their nutrient needs. Harper (1977) points out that the understanding of nutrient demands and nutrient supply of plant populations is greatly complicated by the existence of mycorrhiza. Practically all plants in natural conditions are mycorrhizic, and it is through this symbiotic relationship that nutrient uptake from soil occurs (Gunary 1968, as cited in Harper 1977).

Acid solutions in soil may affect plant growth by checking activity of nitrifying bacteria and all forms of nitrogen-fixing bacteria, thereby preventing the normal decay of tissues as well as limiting the availability of potassium and other soil salts (Weaver 1926). Revegetation potential on strip mined areas is pH dependent (Miles et al. 1973). With a pH below 2.5, root development by either trees or herbs is unlikely; however, with a rise of pH to 3.0, some trees survive but development is very poor (Harabin and Gretszta 1973).

Root Development, Organic Matter Content, and Mulch

The relationship between rainfall, soil moisture, and shoot and root growth was studied on newly excavated Scotland soils of Barbados (Eavis and Cumberbatch 1968, as cited in Eavis and Payne 1969). Plots were either mulched with cut grass or left bare. Sugar cane was planted and fertilizer applied. Root weights at the medium and high levels of fertilizer were about equal on the mulched plots and 2.5 times greater than those on the bare plots. At the low fertilizer level, the average root weights were 1.5 times greater than those on the bare plots. The volume of soil occupied by the roots was greater as the fertilizer rates increased on the mulched plots, and the differences became greater with time.

Buckner (1979) studied the effects of the use of fertilizer and mulch on establishing pine seedlings on severely eroded, heavy clay (Fullerton) and loam (Litz) in east Tennessee near Oak Ridge. Loblolly survived well, grew better than other pine species tested, and consistently responded favorably to treatments of fertilizer and mulch. Pitch pine survived and grew well on both sites, but it was less responsive to treatment. Virginia pine grew better than shortleaf on both sites, but treatment on Litz loam appeared to depress growth. Survival and growth of white and scotch pine were low (Buckner 1979).

Unger and Parker (1976) and Unger (1978) suggest saving soil moisture by using mulches in agricultural fields. Springer et al. (1969) recommend the use of mulch when revegetating roadsides to protect the surface from water erosion; to hold seed, fertilizer, and lime in place; to prevent extremely high or low temperatures in the surface soil; to hold moisture and reduce evaporation; and possibly to supply seed in the form of seed-bearing hay. Weaver (1941) observed that about 85% of the water loss from a stand of big bluestem (Andropogon gerardi) in a Nebraska prairie was by transpiration and about 15% by evaporation from the soil surface. Where big bluestem was pastured, losses by evaporation and transpiration were similar and amounted to about 55% of the level of the unpastured prairie (Kramer 1949). (Big bluestem produced only 57% of the forage in pasture, compared to that under prairie conditions.)

Rooting Depth and Percolation of Moisture Through the Soil

Roots grown in soil eventually die and decay, contributing to the development of the microstructure of the soil and enhancing downward movement of draining water (Colman 1953). Cropped soil was greatly reduced in water-absorbing and water-holding capacity, according to Weaver and Zink (1946).

When no vegetation is present, rain impacts directly on the soil surface, causing puddling or ponding if the soil contains a large percentage of clay, and rapid penetration of water is prevented and runoff and erosion promoted (Weaver and Darland 1949).

Effect of Oxygen and Aeration on Root Penetration

Plants grown naturally in well-drained soils are much more sensitive to the composition of the soil atmosphere than those grown in poorly aerated habitats (Weaver 1926). Certain deep-rooted species like alfalfa are able to grow in an atmosphere having only 2% O_2 (Weaver 1926).

In loose soils (bulk densities of 1.1 g/cm^3), restriction of elongation of excised pea root tips occurred at 30% gas-filled pore space and below; in medium compact soil (1.4 g/cm^3), restriction of root elongation occurred below 22% gas-filled pore space; and in compact soils (1.6 g/cm^3), restriction occurred below 10% (Eavis and Payne 1969). A large number of small pores appeared to be more effective in reducing the effects of liquid barriers around the root than a smaller number of larger pores (Eavis and Payne 1969). Slight compaction of soils seems to increase root development; such compaction may simply convert large pore spaces to more numerous small ones (White 1977).

Soils with less than 10 to 12% of their volume as pore space free of water when the soil is at field capacity are likely to be poorly aerated (Kramer 1949). Root pressure and therefore water uptake are reduced under low oxygen concentrations (Kramer 1949). Although oxygen is consumed in large quantities by roots of growing plants, it appears to be the least likely to be reduced to a limiting level by the growth of neighboring plants, which is due in part to the transport of oxygen from the shoots to the roots (Harper 1977).

Root contributions to CO_2 in soils have been estimated as ranging from insignificant to more than two-thirds of the total CO_2 released in the soil (Witkamp and Frank 1969 as cited in Crapo and Coleman 1972). Weaver (1926) reports that many plants respond to an increase in the CO_2 content of the soil by developing roots that are much shallower and more widely spreading in the surface soil. Decomposition of organic matter and respiration of grass roots produces oxygen and carbon dioxide concentrations in prairie soils that might be unfavorable for the growth of tree roots (Kramer 1949).

Rooting Depth and Soil Moisture

Long (1959) considers the moisture level of soil at which plants wilt (i.e., soil moisture held at a tension of 1.5 MPa (15 bar)], in the different soil layers crucial for explaining root penetration for different crop plants in various soils in Tennessee. An example is the root penetration of alfalfa. It showed a very wide range of rooting depth from 57 cm in Dickson silt-loam, with a hardpan at 0.6 m to 213 cm in well-drained Pennbrook silt-loam. Deep root penetration and large root biomass (3.5 (metric)t/ha) in Pennbrook silt-loam yielded a hay yield of 5.4 (metric) t/ha which was not different from the hay yield of 5.2 (metric) t/ha obtained for alfalfa grown on a different silt-loam (Mountview), where only 0.6% of the roots penetrated deeper than 61 cm and the total root biomass was 6.53 (metric) t/ha. Fertilization and cropping sequence had been similar to both sites. Alfalfa penetrated only up to a depth of 91 cm in a Cumberland loam soil in which tall fescue, as a 2-year-old stand, penetrated up to 122 cm and, as a 4-year-old stand, up to 152 cm.

Al-Ithawi et al. (1980) found that elevated soil moisture levels enhanced soybean yield and increased removal of ^{32}P-labelled phosphate at different soil depths. With sufficient soil moisture, ^{32}P uptake as deep as 91 cm was equivalent to that at shallower depths (Al-Ithawi et al. 1980).

The depth to which conifer sinkers (secondary roots that descend more or less vertically from either the central root complex or from long laterals) descended was influenced strongly by soil moisture conditions (Sutton 1969). Larger root systems are produced in soils that contain an abundance of soil moisture if aeration is good (Kramer 1949).

Roots are found at greater depths in dry soils than in moist soils (Lyr and Hoffmann 1967). Doss et al. (1960) observed that in fine sandy loam with bulk densities of 1.61 to 1.65 g/cm^3, irrigated after 85, 65, and 30% of soil moisture had been lost compared to field capacity, root penetration averaged up to 160 cm, 147, and 122 cm, respectively (averaged from common bermuda grass, coastal bermuda grass, bahia grass, and sericea lespedeza). Common bermuda grass showed the greatest rooting depth and sericea lespedeza, the least (up to 122 cm).

The ratio of roots to shoots tends to be larger when there is a limited supply of water (Kramer 1949). Duncan (1941) found an inverse relationship between available moisture and root growth in relation to shoot growth of seedlings of white oak (Quercus alba) and red cedar (Juniperus virginiana) growing in three soil types with different moisture levels in the Duke Forest. Both types of seedlings exhibited the best root growth in soils having high air capacity, low porosity, and low amounts of available moisture. Gaiser and Campbell (1951) found root concentrations in soils in different stands of white oak significantly related to permanent wilting percentage in the A2 soil horizon. This agreed with Coile's (1937) idea of root capacity of soils, that is, "under certain conditions, a given volume of soil can support only a given amount of absorbing surface" (Coile 1937) or "water-transmitting properties of the soil, jointly with evaporative demand, determine the optimum root density for each situation" (Teare 1977).

Root growth ceases when soil moisture is reduced to 12 to 14% on an oven-dry soil basis or 4 to 6% on an air-dry soil basis (Lyr and Hoffmann 1967). Water deficiency leads to an inhibition of root growth before cessation of shoot growth or any visible injury becomes evident (Lyr and Hoffmann 1967).

White (1975) explains the influence of soil moisture in facilitating root penetration by pointing out that moist soil, drained often, releases additional water if pressure is applied. Such pressure may be applied by roots. The released water flows to adjacent pores and decreases the air-water interface area in these pores. The surface tension is reduced, and the soil is freer to move and flow away from the root (White 1975).

Root Penetration, Bulk Density, Soil Strength, Hardpans, and Bentonite

Weaver and Crist (1922) report that many native species penetrate into the hardpan which is found in soils over much of the Great Plains region. Species that are reported as penetrating deepest are buffalo grass (*Buchloe* sp.), grama (*Bouteloua gracilis*), wire grass (*Aristada purpurea*), psoralea (*Psoralea tenuiflora*)(a legume), milkpink (*Lygodesmia juncea*), and planted tall panic grass (*Panicum virgatum*). Planted bluestem (*Andropogon gerardi*) roots were limited to the depth of moist soil and did not extend beyond the hardpan in the first season. Underground parts of crop plants were usually limited by the hardpan. Even the normally deep-rooted alfalfa was confined to the soils above the hardpan (Weaver and Crist 1922). Scott and Erickson (1964) found alfalfa to penetrate soils with bulk densities of 1.9 g/cm^3 when oxygen was provided in the form of calcium peroxide (CaO_2). However, the taproots were very crooked.

Roots of sudan grass and soybean grown in field cores were more variable than those grown in laboratory-compacted cores (Zimmerman and Kardos 1961). Bulk densities of 1.5 to 1.77 g/cm^3 flattened roots in field cores. Bulk densities of laboratory-compacted soils, which virtually prevent sudan grass and soybean root penetration, varied with soil type and ranged from 1.8 to 2.0 g/cm^3.

Girdling effects in cotton plants caused by hardpan layers have been studied by Taylor et al. (1964a,b) and Mathers and Welch (1964) for the southern Great Plains area. Mathers and Welch (1964) found that 2 to 3% (by weight) moisture loss can change a latent pan to one that severely restricts root growth.

Annotated bibliographies (CBS 1957-1964, 1965-1972) on rooting depth and mechanical resistance of soil indicate that root extension is greatly reduced or ceases at bulk densities of 1.5 g/cm^3 (Scotch pine on upland heaths), 1.6 g/cm^3 (rice seedlings and soybean), 1.8 g/cm^3 (barley, rice), and 1.7 to 1.8 g/cm^3 (cotton). Red clover seedlings were restricted in clay-loams with bulk densities of 1.3 g/cm^3 at 0.2 MPa (2 bar) soil moisture tension, but did not grow at 0.1 MPa (1 bar) soil moisture tension. Taprooted lucerne clover was able to penetrate unweathered shale horizons with bulk densities greater than 1.69 g/cm^3 and as high as 1.9 g/cm^3 when extra oxygen was present.

Soil moisture and aeration, together with bulk density, are important determining factors for root penetration in soils. Soil strength [expressed in megapascals (bars)] takes bulk density and soil moisture into account and is defined as "the ability or capacity of a particular soil in a particular condition to resist or endure an applied force" (Gill and Vanden Berg 1967, as cited in Taylor 1974). Taylor et al. (1966) present data representing effects of various combinations of soil bulk density and soil moisture on soil strength as measured by a force-gauge penetrometer. Depending on the type of soil, soil strength varies with bulk density and soil moisture. All soils show a similar relation between percent of root penetration and soil strength. No taproots penetrate any soil with a measured strength of 2.5 MPa (25 bar) or greater (Taylor et al. 1966). Blanchard et al. (1978) found root growth of pea seedlings to be essentially stopped at 2 MPa (20 bar).

Since the root has plastic properties, its path will generally be along the line of least resistance, and only in fine-grained homogeneous media will the relationship between root penetration and penetrometer measurements be realistic (Gill and Bolt 1955). Eavis et al. (1969) found that the force required for penetration of a penetrometer was 4 to 8 times greater than that required for root penetration. However, Bradford (1980) considers the penetrometer still the most common means of detecting root-restricting zones in soils.

Pfeffer (1893) [as reviewed by Gill and Bolt (1955)] measured axial root pressures of 0.67 to 2.5 MPa (6.7 to 24.9 bar) and radial root pressures of 0.46 to 0.66 MPa (4.6 to 6.6 bar). Taylor and Ratcliff (1969) confirm the correlation between osmotic potential and root growth pressure claimed by Pfeffer. Root growth pressures produced varied from 0.6 to 1.6 MPa (6 to 16 bar) for cotton seedlings, from 0.6 to 2.6 MPa (6 to 26 bar) for pea seedlings, and from 0.5 to 2.2 MPa (5 to 22 bar) for peanut seedlings. Eavis et al. (1969) found that root growth pressures at which root elongation ceases varies with different types of roots. Root growth pressures in pea seedlings did not decrease when oxygen concentration was reduced from 21 to 3%. No reduction in root growth pressure took place in cotton plants when oxygen concentration was reduced from 21 to 8%; however, reduction in oxygen concentration from 8 to 3% reduced average root growth pressures from 1.1 to 0.5 MPa (11 to 5.0 bar).

White (1977) studied compression on roots as moist soil dries. Soil water at the wilting point is held at 1.5 MPa (15 bar) force. Soil dries as roots extract water, increasing soil water tension and root compression. White found reduction of yield in corn, oats, and western wheatgrass directly related to pressure applied from 0.3 or 0.4 MPa (3 or 4 bar) to 1.0 or 1.5 MPa (10 or 15 bar).

Nofziger and Swartzendruber (1976) found that the bulk density of a 50:50 bentonite-silt mixture decreased when wetted. The bentonite-silt column was confined; therefore, the bulk density average remained the same when the wetting front passed through the soil column. Arora et al. (1981) expect the seal densities of the bentonite-shale layer over the waste sites in the White Oak Creek Watershed to be between 1.5 and 1.9 g/cm^3. This bentonite-shale layer is not confined and will decrease in bulk density when wetted.

Hawkins and Horton (1967) planted common bermuda grass as stolons, sericea lespedeza as young plants, and longleaf pine as year-old seedlings on 0.6 m of soil over bentonite layers 2.5 and 10 cm thick. Three hundred-mesh bentonite had been fed into a "cement gun" and sprayed as a 50% water slurry over the soil to form a continuous layer. Cesium-137 was added to the soil below the bentonite. Soil above the bentonite layer was often water saturated. Bermuda grass grew most vigorously, and within 4 months ^{137}Cs was detected in all bermuda plants. Within 6 months ^{137}Cs was detected in all sericea lespedeza plants. Pine seedlings did not grow very well and no ^{137}Cs was detected in them after 24 months.

RADIONUCLIDE MINING

Data on bulk densities and soil strength indicate that, when moist, the bentonite-shale layers over the waste sites may be penetrated by plant roots. Hawkins and Horton (1967) showed that common bermuda grass and sericea lespedeza penetrate through 2.5- and 10-cm bentonite layers and take up buried ^{137}Cs. They suggest that areas must be kept free of any vegetation when bentonite is used to protect radioactive waste.

In general, uptake and turnover of fission products are dependent on (1) the concentration of the fission products in the soil, (2) the species-specific physiological control of nutrient uptake by the plant, and (3) the productivity (or yield) of the different plant species (Auerbach et al. 1959).

^bach et al. (1959) observed that ^{90}Sr and ^{137}Cs levels sampled over a period of 3 years remained essentially the same for herb species (Polygonum sp., Eupatorium, Solidago, Bidens, and Impatiens) and for woody species (Rhus glabra, Salix nigra, Platanus occidentalis, and Fraxinus pennsylvanica) grown on the drained bed of White Oak Lake, a lake that receives runoff from low-level radioactive waste disposal areas. Only one plant community, sericea lespedeza (Lespedeza cuneata), removed more than 1% of the soil burden of radionuclides per surface area sampled. The ^{90}Sr was more readily taken up than was ^{137}Cs. Studies on crops of millet (setari italica), sudan grass (Sorghum sudanense x saccarum), and orange fodder cane (Sorghum vulgare) grown on the White Oak Lake bed showed that differences in concentration of radionuclides were partly accounted for by differences in yield. For example, millet had approximately 25% the yield of orange fodder and 4 times as much ^{90}Sr per gram of plant biomass. The amount of ^{137}Cs accumulated by vegetation reflected the concentrations of ^{137}Cs in the soil: plants with the highest yield had the highest concentration of ^{137}Cs. The ^{60}Co concentration in millet was significantly greater than that in sudan grass or orange fodder, irrespective of yield or concentration in soil.

Through multiple regression analysis, Shanks and DeSelm (1963) found the total ^{137}Cs in the 0- to 5-cm oil layer to be a major contributor to the uptake of ^{137}Cs by the sedge Carex frankii in White Oak Lake bed. Exchangeable ^{137}Cs in the 0- to 15-cm depth contributed significantly to the regression model, while exchangeable calcium, exchangeable magnesium, and pH in the surface 15 cm of soil contributed to the information on cesium availability to plants. Half of the variation in plant ^{137}Cs remained unexplained.

Graham (1958) studied ^{90}Sr and ^{137}Cs uptake by smartweed (Polygonum lapathifolium). Low concentrations of ^{90}Sr in plant tissues were associated with high sodium and high calcium concentrations in the soil. High uptake of ^{137}Cs was associated with a moderately low supply of potassium in the soil.

Duguid (1975) found leaves with high levels of ^{90}Sr on a small sweet gum tree near a liquid waste seepage trench on the White Oak Creek Watershed. He suggests that the substantial uptake of ^{90}Sr may have been caused by the low calcium content of the soil in that area.

CONCLUSIONS AND SUGGESTIONS

INFLUENCE OF VEGETATION ON THE WATER BALANCE OF SOILS

The potential of plant species to influence the water balance in soils is directly related to the rooting depth of the plant. Only under favorable atmospheric conditions and only when roots fully occupy a soil are plant species able to deplete the soil to a water tension of around 1.5 MPa (15 bar) (generally the permanent wilting point).

The drying rate of a soil profile is dependent on the characteristics of the vegetation [e.g., stratification, density, coverage (whether evergreen or deciduous), phenological stage], on the frequency of replenishing soil water, and on solar radiation.

If the soil is occupied by roots to a depth of 60 cm and rainfall averages 132 cm/year, the vegetation type will have no significant influence on the water balance of the soil to the 60-cm depth. Only deep-rooting vegetation can influence the water balance in a watershed under such circumstances.

ROOTING DEPTH, ENVIRONMENTAL FACTORS, AND SUCCESSION

Plant species and varieties have genetically determined root growth characteristics, which may be overriden by environmental factors. Soil moisture, aeration, and bulk density of the soil are determining factors for root penetration. Hardpans in the soil become more penetrable when wet. When roots occupy the same site for a longer period of time, they may penetrate deeper into soil layers; and deeper root penetration can be expected in progressive successional stages. When a high percentage of root biomass is found in the upper layers of the soil, the fraction of the root biomass penetrating deeper soil layers might be physiologically very important in water metabolism and nutrient cycling.

Removal of organic matter buildup (1) is a factor in maintaining a stable vegetation, (2) causes excessive drying out of the topsoil, which reduces root proliferation in the top layer of soil, and (3) enhances deep root penetration.

Root biomass in poor soils is generally greater than in richer soils, while at the same time root proliferation occurs in nutrient-rich zones of soils if sufficiently moist.

IDEAL VEGETATION COVER AND MAINTENANCE

The ideal vegetation cover would require a maximum amount of water uptake to produce dry matter. This can be regulated to a certain extent by fertilization management; for example, nitrogen fertilization increases the water-use efficiency (i.e., decreases water uptake) of grasses.

The nutrient concentration in soils above waste sites should not limit maximum aboveground biomass production but should be such that maximum uptake of water is required to supply the plant with the necessary nutrients for maximum yield. Clipping, mowing, and pruning increase water usage by vegetation as long as root biomass is not affected through insufficient carbohydrate supply.

PLANT SPECIES TO BE CONSIDERED

No one particular species emerges as fulfilling all requirements for the ideal vegetation cover for low-level solid nuclear waste disposal sites.

Vegetation that needs the least maintenance is the type best adapted to the environment where it is established. Natural succession, however, is not desirable on the disposal sites because of the deeper rooting habit of species common to later successional stages. Stabilizing [illegible]e.

[illegible] recommended, not only because of the initial deep-rooting habit of trees but also because the weight of the aboveground biomass may increase the subsidence of the soils over the trenches.

Thicket stages, like the natural successional stage of Japanese honeysuckle-blackberry, trumpet-creeper, grape, and sawbrier, require monitoring for invading deep-rooting species like shortleaf and Virginia pine, oak, sassafras, tulip-tree, etc. Japanese honeysuckle has been reported to form a suitable habitat for invading trees and to eventually become overgrown by canopy trees. A vine-thicket stage of planted kudzu may cause problems similar to those of a honeysuckle-blackberry thicket with regard to checking invading species.

Dense thickets of ornamental shrubs might be acceptable if the shrubs are pruned back occasionally. Fragrant sumac and coralberry are promising; however, they may root deeper than is desirable. _Spiraea_ species are shallow rooted; _Forsythia_ and jasmine will be aesthetically pleasing once they are fully established as mature stands. The competitive ability of ornamental shrubs remains questionable. Prostrate species such as creeping juniper are considered drought tolerant, implying a deep-rooting habit.

Horticultural species are costly to establish and require maintenance in the form of periodic weeding, pruning, and other regular horticultural practices such as pest control.

Herbaceous ornamental species like yellow root, goutweed, bamboo, and lily-turf might be considered singly or in combination with periwinkle, bugleweed, and ivies. Periodic checking of these species for invading species might be easier than checking of shrub thickets.

In the literature on roadside vegetation and coal spoil reclamation, sericea lespedeza and crownvetch are considered the most attractive because they require no maintenance. However, sericea lespedeza mined ^{137}Cs when planted on a 60-cm overburden on top of a bentonite layer covering ^{137}Cs. Other legumes like flat pea, partridge pea, and everlasting pea will form dense mats, but may also root deeply.

Grass covers (currently maintained on the low-level nuclear waste sites) require labor-intensive care, but may provide the least risk of radionuclide uptake as long as drought-resistant grass species are not used. Bermuda grass, bahia grass, and zoysia should be avoided because they are deep-rooted species. Even creeping red and tall fescues, which are reported as "good" with regard to drought tolerance, should be evaluated carefully, as they are potentially deep rooting.

Grass covers help prevent erosion and allow evaporation from the soil surface. Surface fertilization will encourage shallow roots. Reevaluation and a change in the timing of nitrogen fertilization may result in enhancing water uptake by grass covers.

Broomsedge fields will not require fertilization, have a sufficiently shallow root profile, and are relatively stable if mowed once a year (with thatch left on the field). Old-field ecosystems (broomsedge) can be established by application of seed-bearing hay. Seen in the total landscape, they can be considered aesthetically pleasing.

RECOMMENDATIONS

In the next phase of this study, both xeric and mesic sites in existing solid waste disposal areas will be selected for pilot-scale experimental plantings. Recommended plant species to be considered are broomsedge, sericea lespedeza, crownvetch, lily-turf, common periwinkle, bugleweed, ivy, prostrate junipers, creeping honeysuckle, fragrant sumac, and coralberry. The effects of timing of nitrogen fertilization will be considered for study on the present grass covers. Biomass production, species dynamics, vegetation stability, organic matter buildup, soil fertility, and moisture dynamics in the soil profile will be monitored and their ecological interrelationships will be studied. The cost effectiveness of the various management techniques employed will be evaluated through manipulation of the various interrelationships.

The long-term objectives of the research are to provide a sound basis for recommending the type of vegetation cover best suited to each of the solid waste disposal areas.

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APPENDIX A

COMMON NAMES OF SPECIES REVIEWED

Acacia angustissima	Prairie acacia
Acer saccharinum	Silver maple
Aegopodium podograria	Goutweed
Agave virginica	False aloe
Agropyron elongatum	Tall wheatgrass
Agropyron smithii	Western wheatgrass
Agropyron spicatum	Blue-bunch wheatgrass
Agrostis alba	Redtop
Ajuga reptans	Bugleweed
Akebia quinata	--
Ambrosia artemisiifolia	Common ragweed
Ambrosia trifida	Great ragweed
Amorpha fruticosa	Indigo bush
Andromeda polifolia	Bog rosemary
Andropogon elliotii	Elliott's beard-grass
Andropogon gerardi	Big bluestem
Andropogon scoparius	Little bluestem
Andropogon ternarius	Silvery beard-grass
Andropogon virginicus	Broomsedge
Aristida dichotoma	Poverty-grass
Aristida longespica	Three-awn
Aristida oligantha	Few-flowered aristida
Aristida purpurea	Wiregrass

Appendix A (continued)

Arrhenatherum elatius	Tall oatgrass
Aster pilosus	Aster
Avena sativa	Oat
Berberis spp.	Barberry
Beta vulgaris	Sugar beet
Bidens spp.	Bur-marigold
Bouteloua curtipendula	Side-oats grama
Bouteloua gracilis	Blue-grama
Bromus inermis	Smooth bromegrass
Bromus japonicus	Brome-grass
Bromus tectorum	Cheatgrass
Bruckenthalia spiculifolia	Spike heath
Buchloe dactyloides	Buffalo grass
Calluna spp.	Heather
Campsis radicans	Trumpet-creeper
Carex frankii	Sedge
Carya spp.	Hickory
Cassia fasciculata	Partridge pea
Ceanothus gloriosus	Redroot
Ceanothus griseus	Redroot
Ceanothus maratimus	Redroot
Ceanothus ovatus	Redroot
Ceanothus protratus	Redroot
Celtis laevigata	Nettle-tree, hackberry
Cercis canadensis	Redbud

Appendix A (continued)

Chaenomeles spp.	Quince
Chaerophyllum spp.	Chervil
Chimaphila maculata	Pipsissewa
Chrysanthemum leucanthemum	Ox-eye daisy
Clethra acuminata	White alder
Cornus amomum	Silky dogwood
Cornus stolonifera	Red-osier dogwood
Coronilla varia	Crownvetch
Corylus americana	American hazel
Cotoneaster horizontalis	Cotoneaster
Crataegus boyntoni	Hawthorn
Crataegus crus-galli	Cockspur-thorn
Crataegus disperma	Hawthorn
Cynodon dactylon	Bermuda grass
Cytisus scoparius	Scotch broom
Daboecia cantabrica	Irish heath
Dactylis glomerata	Orchard grass
Danthonia compressa	Wild oat-grass
Daucus carota	Wild carrot
Dichondra repens	Dichondra
Digitaria sanguinalis	Crab-grass
Diodia teres	Buttonweed
Diospyros virginiana	Common persimmon
Elaeagnus umbellata	Autumn olive
Eragrostis curvula	Weeping lovegrass

Appendix A (continued)

Erica spp.	Heath
Erigeron canadensis	Horse-weed
Erigeron strigosus	Daisy fleabane
Eucalyptus	Eucalyptus
Eulalia viminea	--
Euonymus fortunei	--
Eupatorium spp.	Thoroughwort
Festuca arundinacea	Alta tall fescue
Festuca elatior	Tall fescue
Festuca rubra	Red fescue
Festuca rubra var. commutata	Chewing fescue
Forestiera ligustrina	Swamp privet
Forsythia suspenza	Forsythia
Fraxinus pennsylvanica	Green ash
Gaultheria spp.	Aromatic wintergreen
Gaylussacia baccata	Black huckleberry
Gaylussacia brachycera	Box huckleberry
Gaylussacia peregrina	Huckleberry
Genista tinctoria	Dyer's greenweed
Glycine max	Soybean
Gnaphalium obtusifolium	Catfoot
Hedera spp.	English ivy
Hemerocallis	Day-lily
Hosta spp.	Plantain-lily
Hydrangea arborescens	Wild hydrangea

Appendix A (continued)

Hypericum calycinum	Rose of Sharon
Impatiens spp.	Jewelweed
Jasminium nudiflorum	Jasmine
Juniperus horizontalis	Creeping juniper
Juniperus virginiana	Red cedar
Kalmia latifolia	Mountain laurel
Lathyrus latifolius	Everlasting pea
Lathyrus sylvestris	Flat pea
Leiophyllum buxifolium	Sand myrtle
Lespedeza bicolor	Bicolor lespedeza
Lespedeza cuneata	Sericea lespedeza
Lespedeza japonica	Japanese lespedeza
Lespedeza stipulacea	Korean clover
Lespedeza striata	Japanese clover
Lespedeza thunbergii	Thunberg lespedeza
Lespedeza virginica	Slender bush-clover
Ligustrum amurense	Amur privet
Lindera benzoin	Spicebush
Linum usitatissimum	Common flax
Lippia canescens	Frog-fruit
Liriodendron tulipifera	Tulip-poplar
Liriope spicata	Lily-turf
Liquidambar styraciflua	Sweet gum
Lolium multiflorum	Annual rye
Lolium perenne	Perennial rye

Appendix A (continued)

Lonicera japonica	Japanese honeysuckle
Lonicera maackii	Amur honeysuckle
Lonicera morrowi	Morrow honeysuckle
Lonicera pileata	Honeysuckle
Lonicera prostrata	Honeysuckle
Lonicera tatarica	Tartarian honeysuckle
Lotus corniculatus	Birdsfoot trefoil
Lycium chinense	Chinese matrimony-vine
Lygodesmia juncea	Milkpink
Maclura pomifera	Osage orange
Medicago sativa	Alfalfa
Melilotus alba	White sweet clover
Melilotus officinalis	Yellow sweet clover
Menispermum canadense	Moonseed
Ophiopogon japonicus	Dwarf lily-turf
Pachysandra procumbens	Allegheny-spurge
Pachystima canbyi	Cliff-green
Panicum antidotale	Blue panic grass
Panicum clandestinum	Deertongue
Panicum commutatum	Variable panic grass
Panicum stipitatum	Tall flat panic grass
Panicum virgatum	Tall panic grass
Parthenocissus quinquefolia	Virginia creeper
Paspalum dilatatum	Dallis grass
Paspalum notatum	Bahia grass

Appendix A (continued)

Petalostemum	Prairie clover
Phalaris arundinacea	Reed canary grass
Phleum pratense	Common timothy
Pinus echinata	Shortleaf pine, yellow pine
Pinus rigida	Pitch-pine
Pinus strobus	White pine
Pinus taeda	Loblolly
Pinus virginiana	Virginia pine, Jersey
Plantago aristata	Bracted plantain
Plantago lanceolata	Ribgrass
Platanus occidentalis	Sycamore
Poa compressa	Canada bluegrass
Poa pratensis	Kentucky bluegrass
Polygonum affini	Border jewel
Polygonum bistorta	Snake weed
Polygonum cuspidatum	Japanese fleeceflower
Polygonum lapathifolium	Smartweed
Polygonum reynoutria	Dwarf fleeceflower
Potentilla canadensis	Common cinquefoil
Potentilla fruticosa	Shrubby cinquefoil
Prunus besseyi	Sand cherry
Prunus serotina	Black cherry
Prunus virginiana	Choke cherry
Psoralea tenuiflora	Few-flowered psoralea
Pueraria lobata	Kudzu

Appendix A (continued)

Pyrus melanocarpa	Black chokecherry
Quercus alba	White oak
Quercus macrocarpa	Bur-oak
Rhododendron carolinianum	Carolina rhododendron
Rhododendron catawbiense	Purple rhododendron
Rhododendron maximum	Great laurel
Rhus aromatica	Fragrant sumac
Rhus copallina	Shining sumac
Rhus glabra	Smooth sumac
Rhus radicans	Poison ivy
Robinia fertilis	Bristly locust
Robinia pseudoacacia	Black locust
Rosa carolina	Wild rose
Rosa nitida	Northeastern rose
Rosa setigera	Climbing rose
Rubus allegheniensis	Sow-teat blackberry
Rubus enslenii	Dewberry
Rubus flagellaris	Bramble
Rubus occidentalis	Black raspberry
Rumex acetosella	Sheep sorrel
Salix nigra	Black willow
Sambucus canadensis	American elder
Sasa pumila	Dwarf bamboo
Sasa variegata	Dwarf bamboo
Sasa veitchi	Dwarf bamboo

Appendix A (continued)

Sassafras albidum	White sassafras
Senecio smallii	Small's squawweed
Setaria spp.	Millet
Smilax glauca	Sawbrier
Solidago altissima	Tall goldenrod
Sorghastrum nutans	Indian grass
Sorghum bicolor	Sorghum
Sorghum sudanense	Sudan grass
Sorghum vulgare	Orange fodder cane
Spiraea x billiardi	Spiraea
Spiraea cantoniensis	Spiraea
Spiraea douglassii	Spiraea
Spiraea x vanhouttei	Spiraea
Sporobulus heterolepis	Northern drop-seed
Symphoricarpos orbiculatus	Coralberry
Trifolium ambiguum	Kura clover
Trifolium incarnatum	Crimson clover
Trifolium medium	Zigzag clover
Trifolium repens	White clover
Trifolium pratense	Red clover
Trifolium procumbens	Low hop-clover
Triticum aestivum	Wheat
Ulmus alata	Winged elm
Vaccinium constablaei	Bush blueberry
Vaccinium corymbosum	Tall blueberry

Appendix A (continued)

Vaccinium vitis-idaea	Mcuntain-cranberry
Verbesina occidentalis	Crown-beard
Veronica spp.	Hebes
Viburnum cassinoides	Witherod
Vicia spp.	Vetch
Vinca minor	Common periwinkle
Vitis conerea	Grape
Xanthorhiza simplicissima	Shrub-yellowroot
Zoysia japonica	Zoysia grass

Plant species other than grasses follow nomenclature of Gray's Manual of Botany (Fernald 1950). Grass species names follow nomenclature used by Hitchcock (1950).

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171-197. Technical Information Center, Oak Ridge, TN 37831 not used. Bermuda grass, bahia grass, and zoysia should be avoided. Even creeping red and tall fescue are reported as "good" with regard to drought tolerance, implying potentially deep rooting.

Grass cover prevents erosion and allows evaporation from the soil surface. Surface fertilization will encourage shallow roots. Reevaluating and changing the timing of nitrogen fertilization may result in enhancing water uptake by the grass cover.