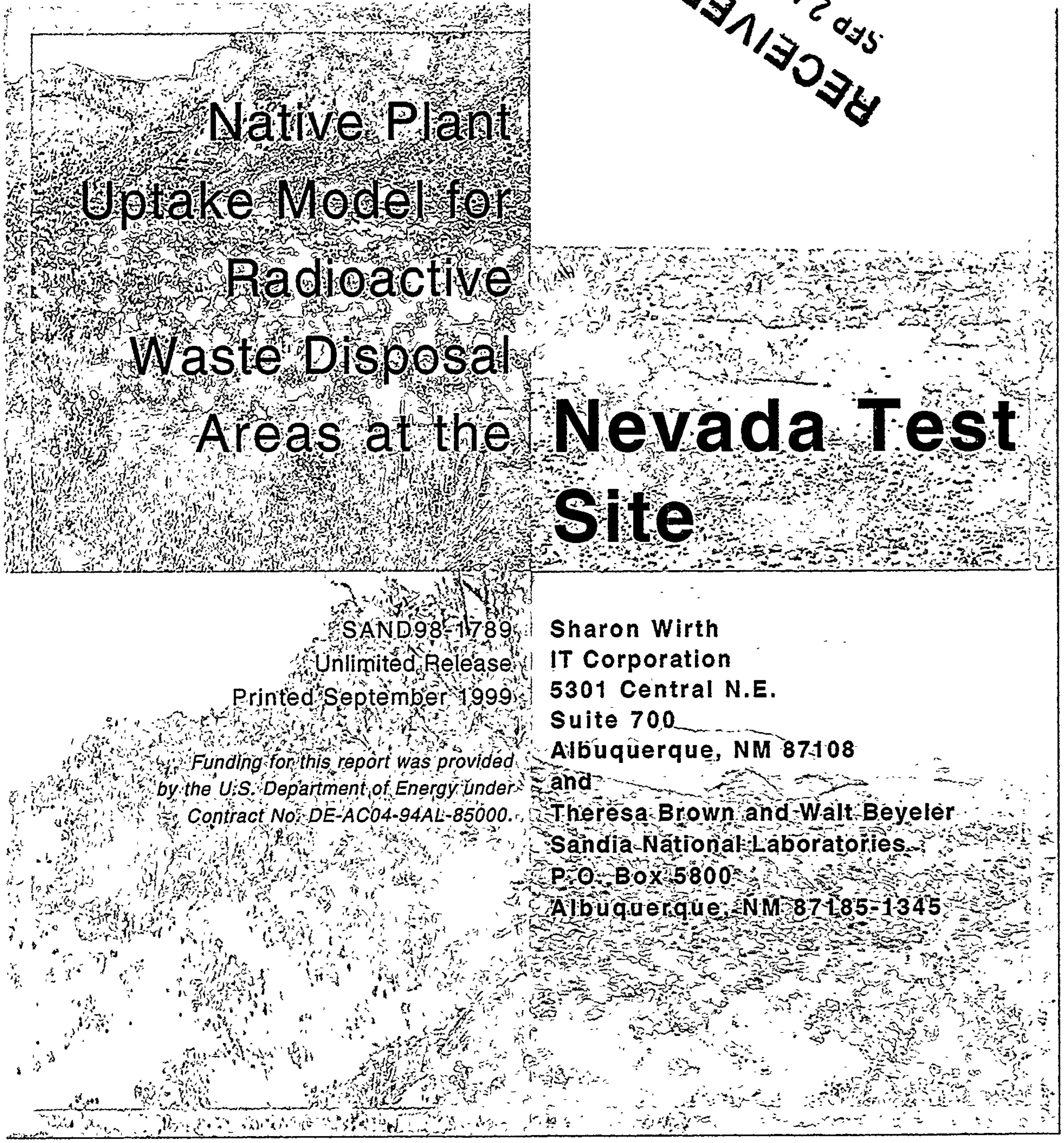

Native Plant Uptake Model for Radioactive Waste Disposal Areas at the Nevada Test Site

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List of Abbreviations/Acronyms

Ac	actinium
Am	americium
ANP	annual net primary productivity
ASC	annual standing crop biomass
°C	degrees Celsius
Cl	chlorine
cm	centimeter(s)
CR	concentration ratio
Cs	cesium
GSD	geometric standard deviation
ha	hectare(s)
IQR	interquartile range
kg	kilogram(s)
m	meter(s)
m^2	meter(s) squared
m^3	meter(s) cubed
mg	milligram(s)
Np	neptunium
NTS	Nevada Test Site
PA	Performance Assessment
Pa	protactinium
Pb	lead
pCi	picocurie(s)
pdf	probability distribution function
Pu	plutonium
Ra	radium
RWMS	Radioactive Waste Management Site
Sr	strontium
Tc	technetium
Th	thorium
TRU	transuranic
U	uranium
µCi	microcurie(s)
yr	year(s)

1.0 Introduction

This report defines and defends the basic framework, methodology, and associated input parameters for modeling plant uptake of radionuclides for use in Performance Assessment (PA) activities of Radioactive Waste Management Sites (RWMS) at the Nevada Test Site (NTS). PAs are used to help determine whether waste disposal configurations meet applicable regulatory standards for the protection of human health, the environment, or both.

Plants adapted to the arid climate of the NTS are able to rapidly capture infiltrating moisture. In addition to capturing soil moisture, plant roots absorb nutrients, minerals, and heavy metals, transporting them within the plant to the above-ground biomass. In this fashion, plant uptake affects the movement of radionuclides. The plant uptake model presented reflects rooting characteristics important to plant uptake, biomass turnover rates, and the ability of plants to uptake radionuclides from the soil. Parameters are provided for modeling plant uptake and estimating surface contaminant flux due to plant uptake under both current and potential future climate conditions with increased effective soil moisture. The term "effective moisture" is used throughout this report to indicate the soil moisture that is available to plants and is intended to be inclusive of all the variables that control soil moisture at a site (e.g., precipitation, temperature, soil texture, and soil chemistry). Effective moisture is a concept used to simplify a number of complex, interrelated soil processes for which there are too little data to model actual plant available moisture.

The PA simulates both the flux of radionuclides across the land surface and the potential dose to humans from that flux. Surface flux is modeled here as the amount of soil contamination that is transferred from the soil by roots and incorporated into aboveground biomass. Movement of contaminants to the surface is the only transport mechanism evaluated with the model presented here. Parameters necessary for estimating surface contaminant flux due to native plants expected to inhabit the NTS RWMSs are developed in this report. The model is specific to the plant communities found at the NTS and is designed for both short-term (<1,000 years) and long-term (>1,000 years) modeling efforts. While the model has been crafted for general applicability to any NTS PA, the key radionuclides considered are limited to the transuranic (TRU) wastes disposed of at the NTS.

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2.0 NTS Ecological Setting

2.1 Hydrology

The climate at the NTS disposal facilities is typical of the upper Mojave Desert, with average daily temperatures ranging from 2 degrees Celsius (°C) in January to 24°C in August. Average annual precipitation is 12.5 centimeters (cm) with a range from 3 to 23.4 cm (French 1993). Peak annual precipitation periods occur in the winter. Smaller precipitation peaks occur in the summer. Precipitation is highly variable, typically occurring as regional, long duration, low intensity winter storms and isolated, short duration, intense summer thunderstorms.

All NTS RWMSs are founded in the thick, arid alluvium of the topographic basins. Groundwater is approximately 235 meters (m) below the land surface (REECo 1994). The limited precipitation, coupled with generally warm temperatures and low humidities, results in a hydrologic system dominated by evapotranspiration. The movement of water within this 235 m unsaturated zone can be subdivided into two zones, the near-surface zone and a deeper vadose zone.

The near-surface zone is the hydrologically dynamic region of the unsaturated alluvium. In this zone, infiltrating moisture is quickly removed by evapotranspiration. The balance of these forces is such that measurable infiltration from precipitation rarely occurs deeper than 2 m (Tyler et al. 1996 and Shott et al. 1998). The average volumetric moisture content in the near-surface zone in areas receiving only aerially distributed moisture is very low, ranging from 1 to 3 percent, though saturation is achieved periodically after precipitation events. In areas where precipitation runoff is captured or channeled, such as in craters and along washes, there can be deeper infiltration and higher average near-surface volumetric moisture contents.

In comparison to the dynamics of the near-surface zone which receives periodic pulses of moisture from precipitation, the deeper vadose zone is hydrologically "inactive." Between a depth of 2 and 35 m, the alluvium shows no measurable change in moisture content over time, low moisture contents (average volumetric moisture content from 8 to 13 percent), and decreasingly negative matrix potential with depth; these observations indicate pore water moves upward at a steady and very slow rate in the vadose zone.

2.2 Physiography and Ecology

The information on the NTS ecology presented in this section is summarized from Beatley (1976). The NTS is located at the interface of the northern extent of the warm Mojave Desert and the southern limit of the cooler Great Basin Desert (Figure 1). The area where these

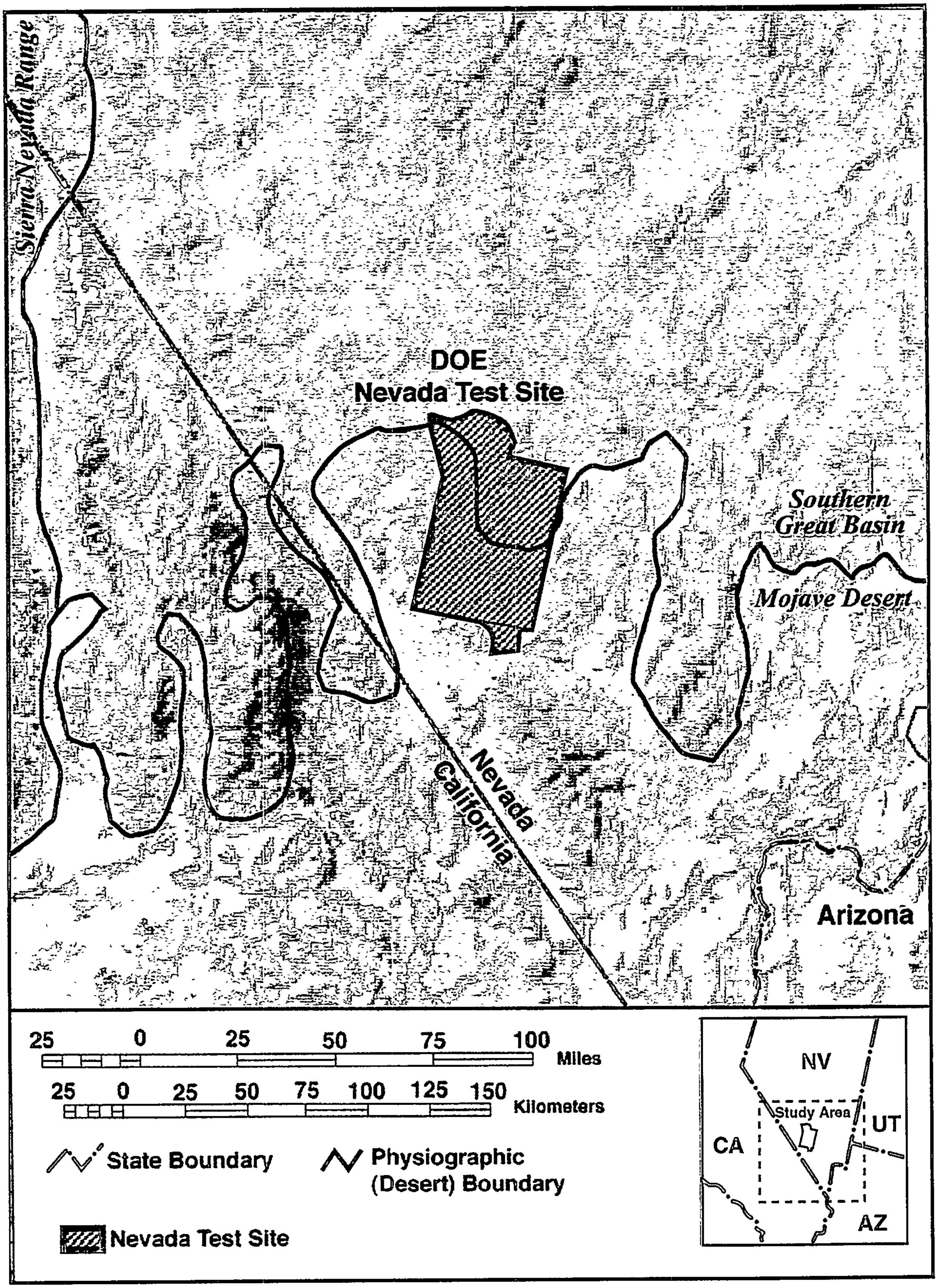

Figure 1

Physiographic Location of Nevada Test Site two deserts overlap is called the Transition Desert. Mojave and Transition Desert communities occupy nearly all the land surface at the NTS below 1,500 m elevation, which includes about two-thirds of the area within the NTS boundaries. The remainder of the NTS area is above 1,500 m elevation and vegetation at these higher elevations belongs mostly to the Great Basin Desert, including the drainage basins and their surrounding mountains in the northern portion of the NTS.

Overall controlling factors of the warm desert communities are the timing and amounts of individual precipitation events, with which most biological activity is synchronized. In the higher regions of the warm deserts and in most of the Great Basin Desert there are similar precipitation patterns as the warm deserts, but the rains occur in greater amounts and under conditions of lower temperatures, leading to a carryover of significant quantities of soil moisture from one period to the next. In these cooler areas, biological activity is more synchronized with seasons of higher temperatures than with the periods of rainfall.

2.3 Plant Ecology

The NTS is probably best characterized as a mosaic of communities in which the dominant and codominant species vary from site to site. It is the relative dominance of different shrubs, or shrubs and trees, that tends to define community boundaries, rather than the presence or absence of non-shrub species. Species composition is considered a site characteristic that does not change from year to year and the number and sizes of individual plants within a population tend to fluctuate within a usually narrow range. The communities are best defined as climax communities in that they are self-perpetuating and in equilibrium with the present climate and soils of the sites they occupy. Population sizes within the communities fluctuate within a range, as expressions of climatic fluctuations.

2.3.1 Shrubland Communities

The current plant community at low elevations within the NTS is desert shrubland. Higher elevations support either shrubland species adapted to relatively cooler and wetter conditions or woodland species. The vegetation has been extensively studied and is well characterized (Beatley 1962, Beatley 1965a, Beatley 1965b, Rickard and Beatley 1965, Beatley 1967, Beatley 1969, Beatley 1975, Beatley 1976, Wallace and Romney 1976, and Hunter and Medica 1989). A photograph of a typical Mojave Desert shrubland is shown in Figure 2.

2.3.2 Woodland Communities

At higher, cooler elevations in the NTS, shrub dominance gives way to tree dominance. At the lowest elevations, desert shrub intergrades with piñon-juniper (*Pinus monophylla-Juniperus*

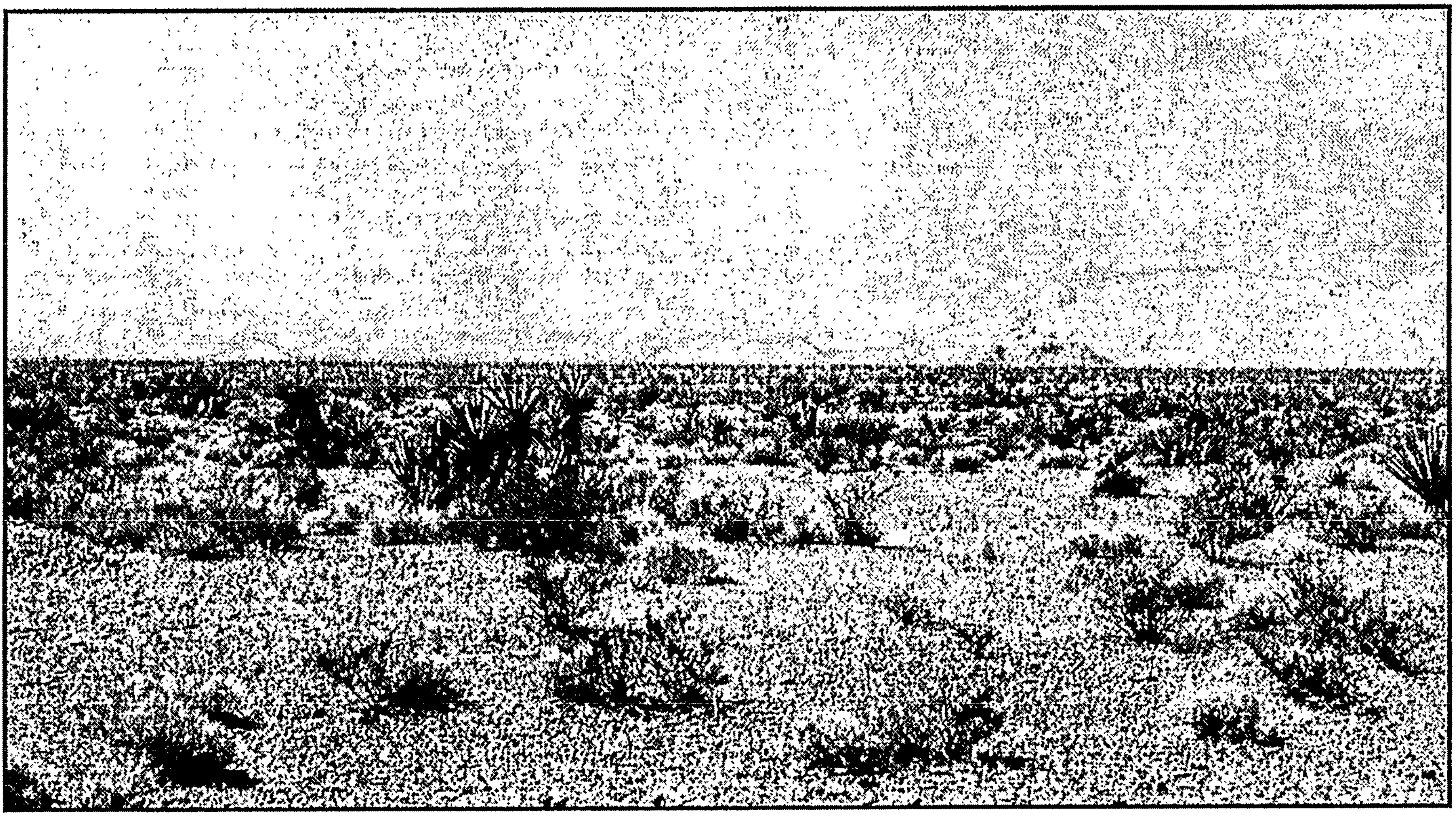

Figure 2

Mojave desertscrub east of Spring Valley Mountains, Clark County, Nevada, ca. 1,220 m elevation. A Creosotebush (*Larrea tridentata*)-Bursage (*Ambrosia dumosa*) series with yuccas present (*Yucca schidigera, Y. baccata, Y. brevifolia*) (Figure 90; Brown 1982)

osteosperma) woodland at approximately 1,800 m. The piñon-juniper woodland gives way to other communities near 2,200 m, the composition of which differs from site to site. Within the piñon-juniper woodlands themselves, relative species dominance varies as a function of elevation, which can be primarily attributed to differences in the availability of soil moisture from low to high elevations. Across one continuous local elevational gradient, juniper has greater amplitude in distribution than piñon, usually due to the extension of juniper into lower and more xeric elevations (Woodin and Lindsay 1954 and Barnes and Cunningham 1987).

Within narrow elevation ranges, slope and aspect can also drive the relative dominance of junipers and piñons, with junipers more prevalent on warmer, drier, south-tending slopes. Physiological studies show that juniper is the more drought-resistant species and that piñon distribution is limited by its lack of water stress tolerance (Barnes and Cunningham 1987, Wilkins and Klopatek 1987, and Breshears 1993).

A piñon-juniper woodland is defined as an area where the dominant woody, non-shrub species is juniper, piñon, or both. As described in this section, the woodlands being proposed as analogues for potential future communities develop and persist under relatively dry conditions at sites currently receiving annual precipitation of only 25 to 33 cm. It should be noted that these are not woodlands with massive trees and lush, multiple layers of undergrowth, a future scenario that is almost entirely implausible in the next 1,000 to 10,000 years at the low elevations of the NTS. At the NTS, these woodlands are, in general, sparsely vegetated, with a tree canopy coverage of less (often much less) than 35 percent. Paleorecords of the NTS region show that it is probable to assume juniper and piñon-juniper woodlands can inhabit even the lowest elevations at the NTS, given appropriate soil moisture conditions (Brown et al. 1997a). A piñon-juniper dominated community is shown in Figure 3.

2.3.3 Ephemeral Wetlands

There are a number of low elevation sites at the NTS with elevated, seasonal soil moisture conditions. Within these sites the vegetation differs markedly from the surrounding shrubland (Beatley 1976 and Hansen et al. 1997). At some of these sites, wetland species (e.g., rushes and sedges) thrive, while at others, the wetter environment supports tree species, including some species that are usually associated with even wetter riparian systems (e.g., tamarix). The persistence of trees and wetland species at these sites with seasonally elevated soil moisture points to the impressive ability of desert-adapted plants to take advantage of enhanced water resources.

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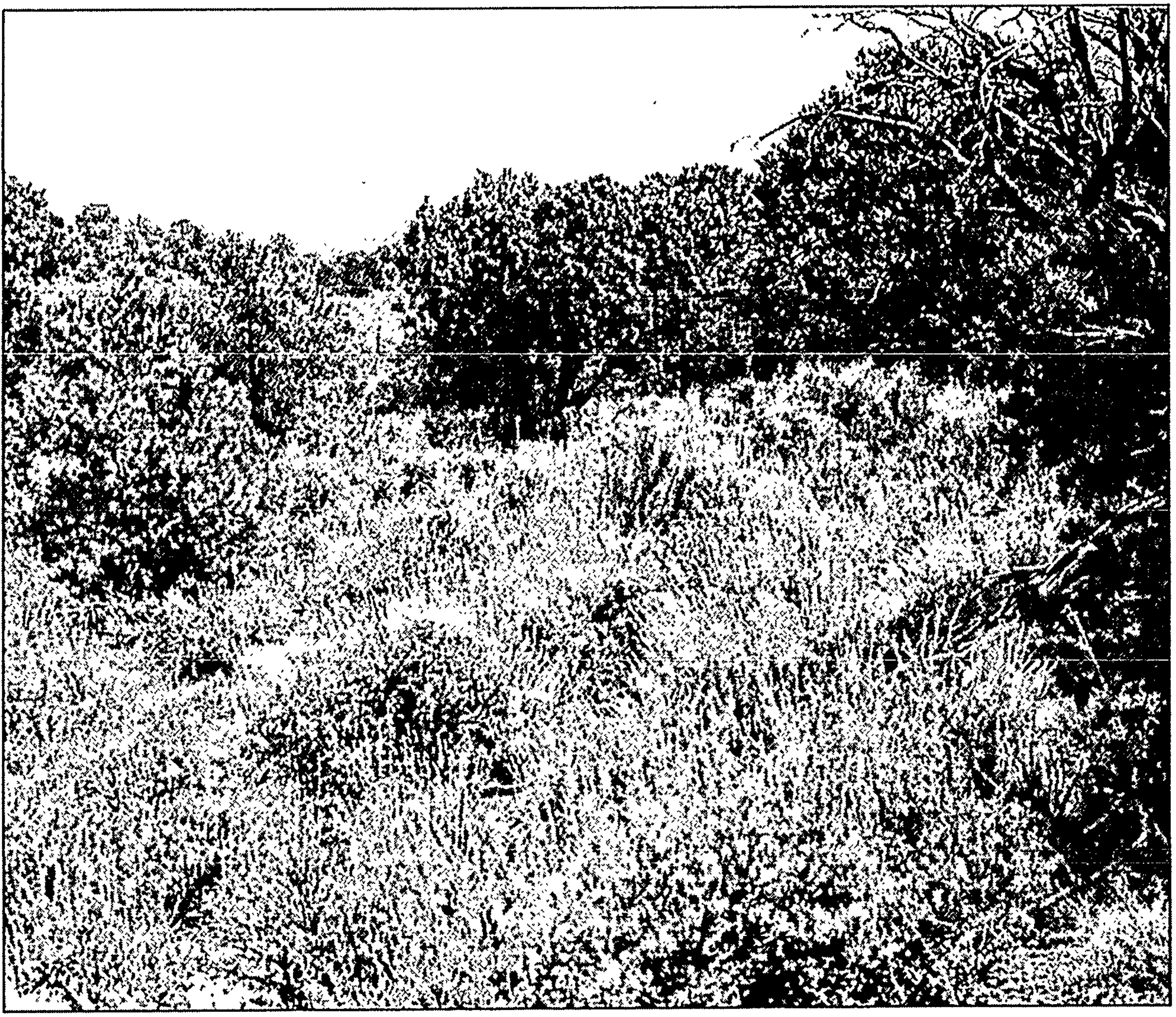


Figure 3

Piñon (*Pinus edulis*) dominated Great Basin conifer woodland on Fish Tail Mesa, Kaibab National Forest, Arizona ca. 1,585 m elevation. The major understory species on this ungrazed site is Big Sagebrush (*Artemisia tridentata*) (Figure 25; Brown 1982)

2.3.4 Community Types and Plant Functional Units

Two types of plant communities are being considered:

(1) a community comprised of species that are currently present in low elevation shrublands; and

(2) a community comprised of species that might develop under future conditions of increased effective moisture, assuming the wetter conditions could support woodland species found in the nearby mountain ranges and/or wetland species such as rushes, sedges, and trees typically found in areas channeling or capturing run on (e.g., washes and depressions).

Species within each community were grouped by the following four lifeforms to avoid excessively cumbersome analyses and computations, and to simplify the data collection and presentation: trees, shrubs/subshrubs, herbaceous perennials, and annuals. Trees and species that belong to the specialized habitats with elevated soil moisture are included only under future conditions. The remaining three lifeforms are included under both current and future conditions.

Lifeform groups are "functional units" because species within the units tend to operate similarly (Walter 1971 and Wilcox and Breshears 1995). This categorization of plants is useful for describing plant communities at the NTS as it is consistent with numerous regional studies indicating lifeform categories appropriately group similarly behaving species (Everett and Sharrow 1985 and DeLucia and Schlesinger 1991). Other regional studies also support the idea that the functionality of community components more appropriately defines a community than the specific species involved (Johnson and Mayeux 1992).

This document provides the data necessary to determine parameter values for shrubland species currently growing at the NTS and woodland and wetland species given greater effective moisture than current-day conditions in the low elevations of the RWMSs. It is up to the PA analyses to implement the model, including the timing and probability of conditions of enhanced moisture—whether these are due to the focusing of infiltration, climate change, or both.

Published data were used to develop model parameters. Wherever possible, data were taken from Mojave Desert, Great Basin Desert, juniper, and piñon-juniper studies that mirrored as many aspects of the NTS as possible. Data were found for some species of each lifeform for each model parameter. The data for each lifeform are separated into data sets representing current and future communities. "Current" includes data for species present in the low elevation shrublands. "Future" includes data for species found in the higher elevations and specialized habitats with increased effective moisture plus data for all low elevation species. This model assumes the future community could contain any combination of species found within the various NTS ecosystems across the entire range of potential future moisture conditions. Details of the assumptions of current and future communities can be found in Brown et al. (1997a).

3.0 Plant Uptake

3.1 Overview

As presented in Chapter 1, plant activity provides a potential pathway for moving radionuclides from the subsurface to the land surface. The conceptual model of radionuclide release due to plant uptake begins by radionuclide absorption from the soil by plant roots, followed by radionuclide transport in the plant to the above-ground vegetative portions of the plant. A simple schematic of the uptake model is shown in Figure 4, explained below.

Contaminant transport from the soil is treated as a bulk flow process and is similar to that described by Murphy (1993). This model is designed to estimate the concentration in vegetation as a function of the soil concentration in the soil layers from which plant roots access water and nutrients, weighted by the extraction of such resources by plant roots. The process of uptake is dynamic, depending not only on soil resources, but also on a plant's need for soil resources and its ability to extract those resources from the soil.

The conceptual model of plant uptake has three main components (Figure 4):

- Plant rooting characteristics. The near-surface soil layers contain the majority of roots to capture transient water infiltration.
- Plant concentration ratios (CR) of radionuclides, which are parameters used in an empirical model of the amount of radionuclides transferred from the soil to aboveground biomass as a function of the total contaminant mass in the soil (sorbed and liquid); and
- Plant biomass production and turnover.

This conceptual model is essentially the same as that used to model plant uptake in all NTS PAs (Shott et al. 1995 and 1998, Winkel et al. 1995, and Brown et al. 1997b). However, many model features are unique to this model, including treatment of parameter and model uncertainty, specific data used, and the model's applicability to both current and potential future conditions.

Plant uptake can be modeled mathematically as a function of soil depth, built from depth-dependent functions of the presence and activity of roots, radionuclide concentrations, and the amount of biomass produced by plants. It is also a "community scale" model in that it sums the contaminant uptake for all plant types within the community (e.g., annuals), defined simply as the assemblage of plants occupying the site at a specific point in time.

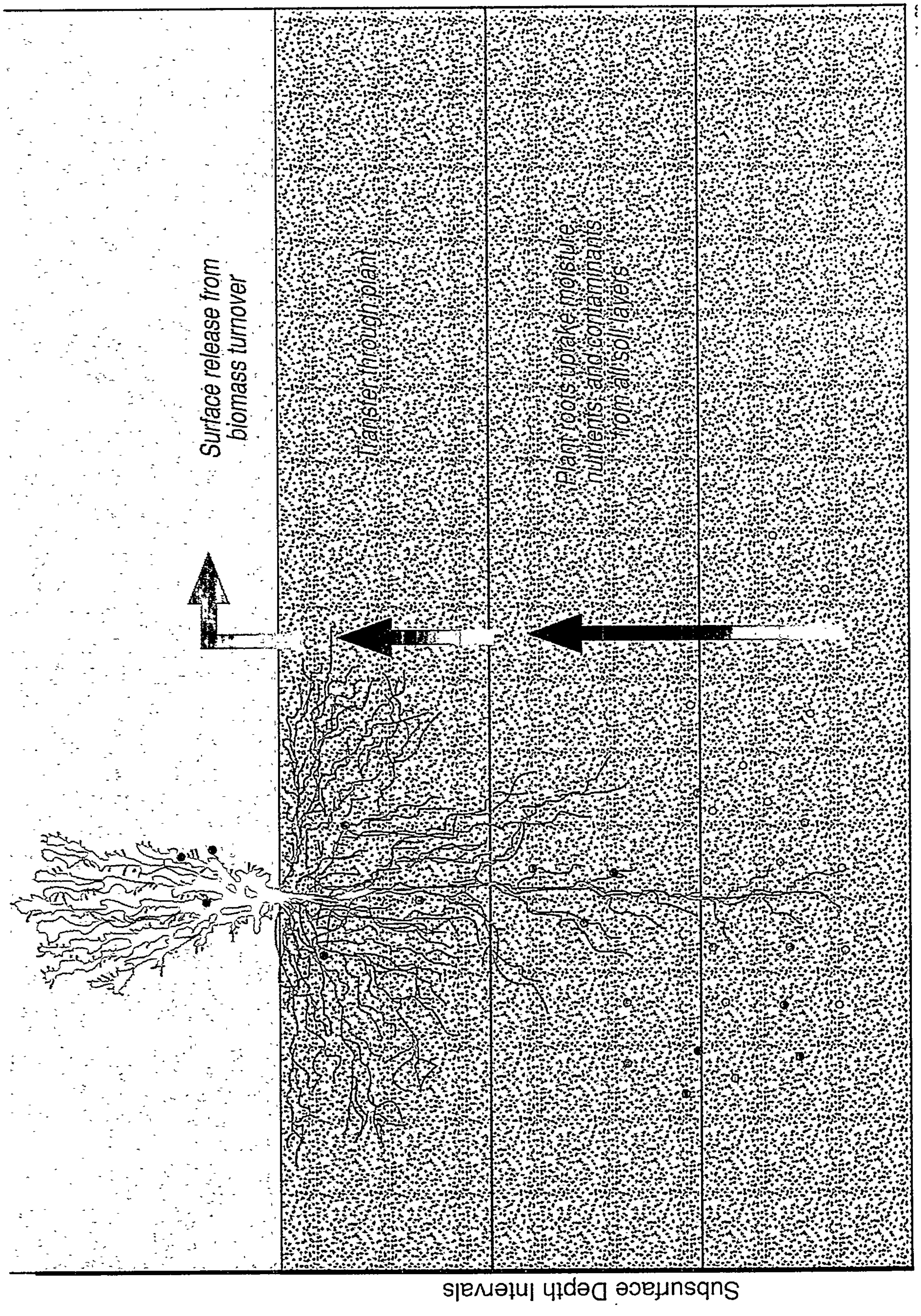


Figure 4
Conceptual Model of Uptake, Transfer, and Release by Plants

3.2 Conceptual Model

The process of root uptake of soil resources is a function of both the distribution of roots with depth and the distribution of resources in the soil. Because roots and soil resources are concentrated in the near-surface layers, the highest amount of extraction occurs in these layers. Figure 5 illustrates how uptake is simulated, given what is known of plant roots and the relative uptake by roots at different depths. The model presented here uses a two-phased approach to simulate two known characteristics of roots relevant to plant uptake: (1) root length and mass decrease with increasing soil depth, and (2) the majority of extraction of soil resources by roots occurs in near-surface soil layers (Figure 5a). Also included are components to estimate the concentration of radionuclides expected in plant tissues as a function of soil concentrations and the annual amount of aboveground biomass produced (Figure 5b and 5c). The actual data used and defense for parameter distribution choices of each model component are detailed in Chapters 4 through 6.

If known, root densities can be used to directly estimate extraction with depth. However, data for root densities with depth are scarce and the data available describe maximum plant root lengths, not root density. Both root density and root lengths are largely controlled by resource availability and follow similar patterns with depth. That is, roots tend to terminate more readily in the near-surface layers where resources are available than they do at depth, where resources are more scarce. Figure 6 illustrates this, using shrub maximum root lengths as an example. Data on maximum root length and the knowledge that roots extract more resources near the surface than at depth are combined to develop a distribution that describes relative extraction rates by roots. Relative extraction rates are then used to estimate the relative amount of biomass that is supported by resources that are extracted from the soil by roots from any soil depth. In summary, the model is designed to account for the fact that roots in the near-surface soil layers contribute more to biomass production than roots deeper in the soil.

3.3 Numerical Model

Radionuclide release due to plant uptake is modeled as a product of the concentration-dependent rate of mass transfer from the soil to the plant, transport within the plant from the point of uptake, and eventual death of the plant (or shedding of plant parts), releasing radionuclides to the land surface. Mathematically, plant uptake of a radionuclide *i* by plant community *c* is described as:

$$Q_{pi} = \int_{z} U_{ci}(z)\ m_i(z)\ dz \qquad \text{(Eq. 1)}$$

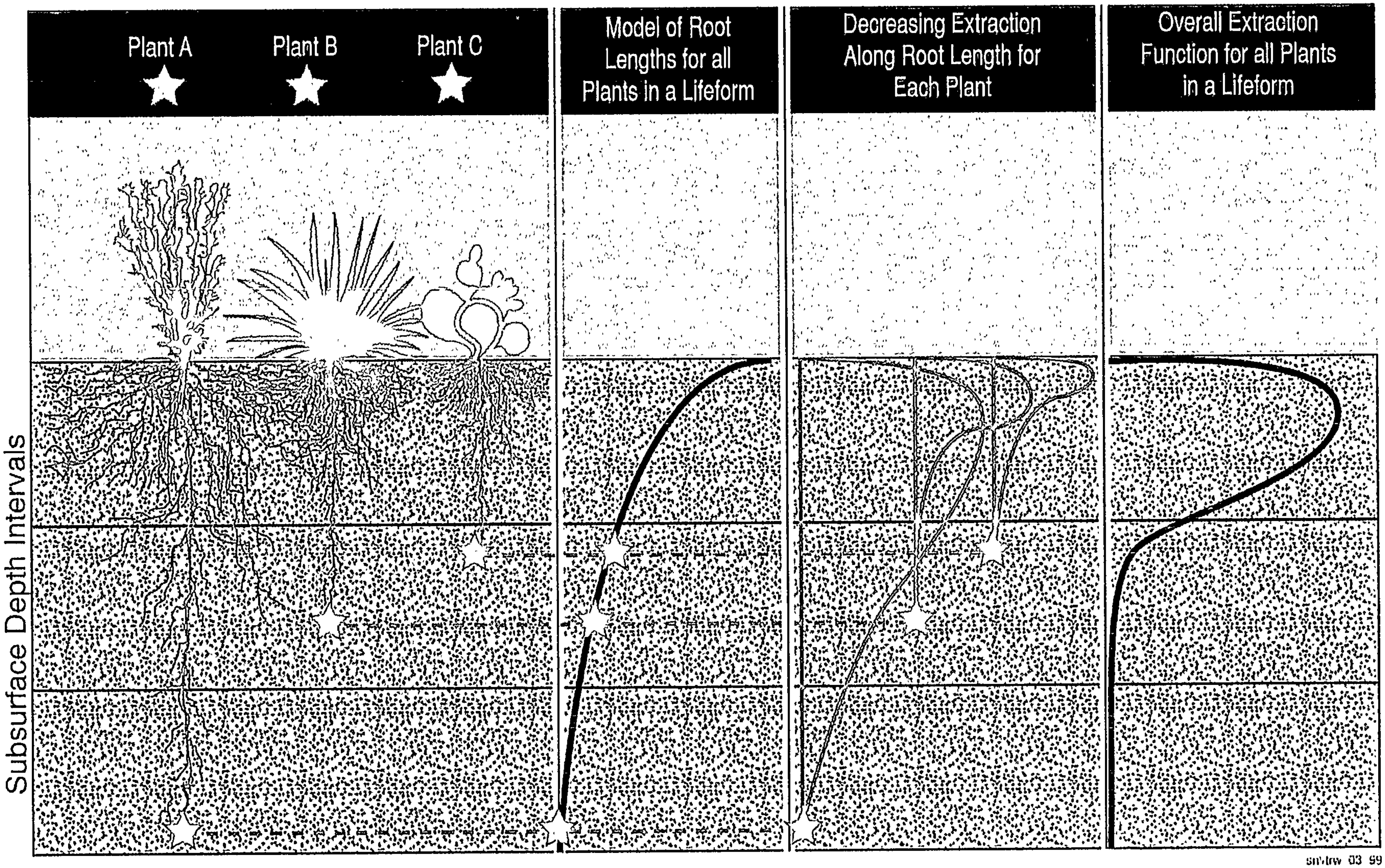
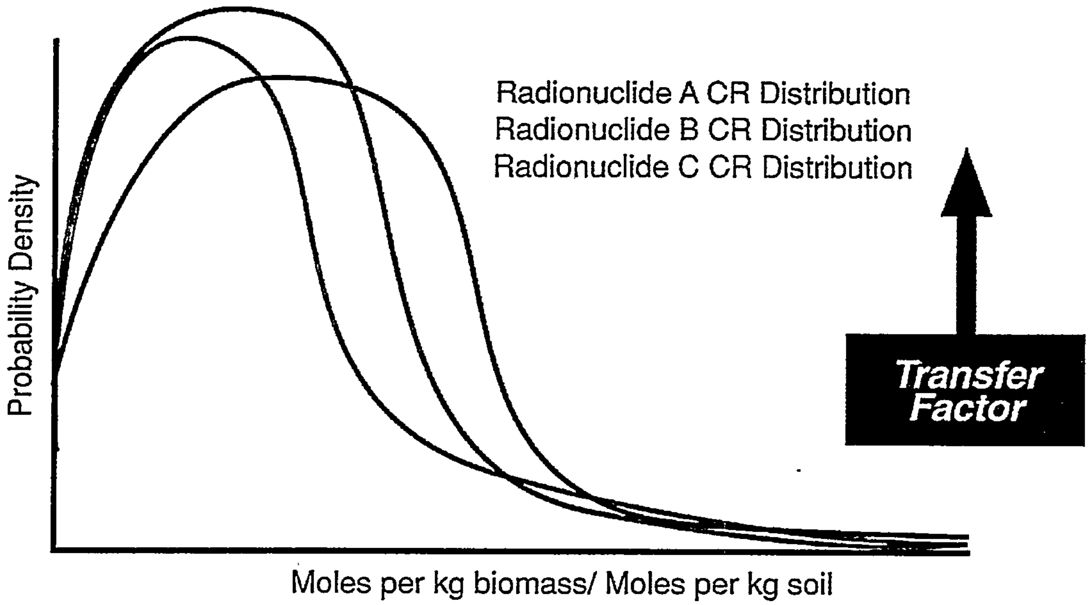
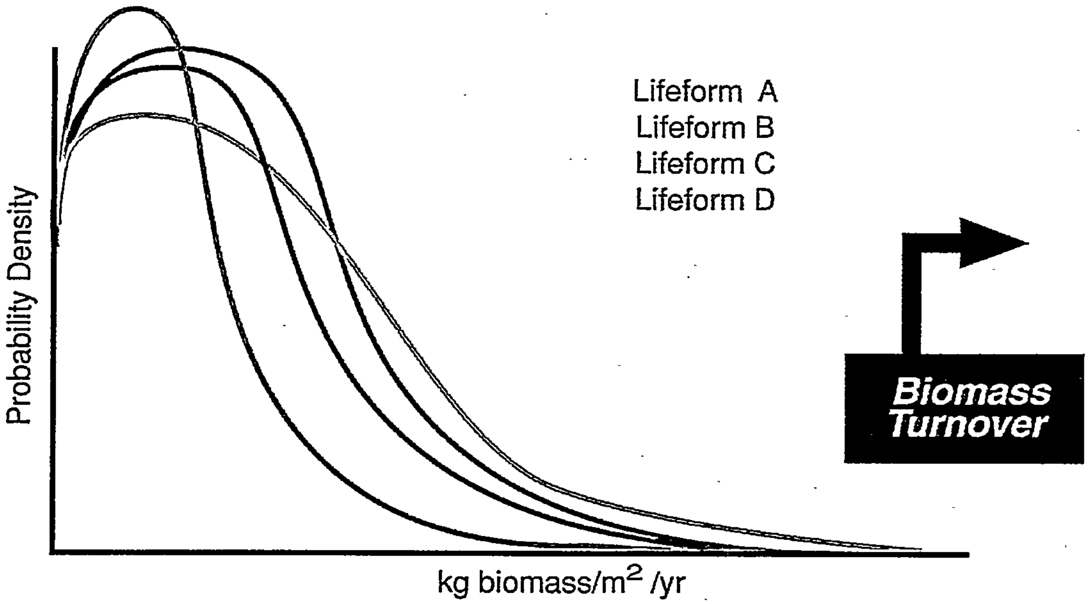


Figure 5a
Simulating Uptake as a Function of Root Length and Extraction



5b

Simulating Uptake as a Function of Concentration Ratios



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Simulating Uptake as a Function of Biomass Turnover

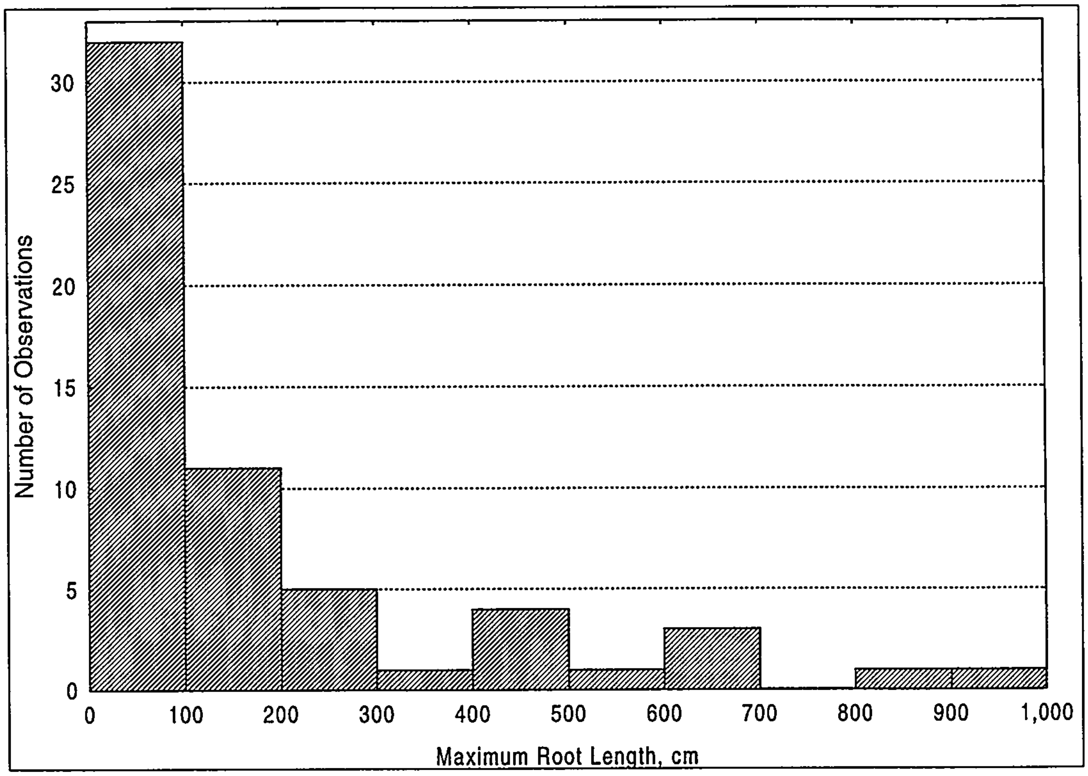

Figure 6

Frequency of Maximum Root Lengths for Shrubs (lengths ≤ 1,000 cm)

where

Q_{ci} = total flux of radionuclide *i* due to plant uptake, in moles removed from soil/(m^2 yr);

$U_{ci}(z)$ = transfer factor describing the rate of removal of radionuclide *i* by plants per unit soil concentration at depth *z*, in moles in plant/yr/m^3/moles in soil/m^3, and

$m_i(z)$ = total mass density of radionuclide *i* at depth *z*, in moles in soil/m^3.

As described in the previous section, U_{ci} varies with depth z, reflecting variations in plant root mass and resource availability. The model does not vary with time the rate of radionuclide removal for a unit soil concentration and thus, U_{ci} represents the expected long-term average behavior of plants within a particular community. Community changes over time are modeled using different transfer factor functions, denoted by the subscript "c." U_{ci} is treated as a random variable with a probability distribution that describes uncertainty about its actual value. The probability distribution for U_{ci} is developed using the functional decomposition detailed below, which relates the value of U_{ci} to other properties of the plant community.

The plant community is divided into a number of lifeform groups (n_g). Each lifeform (j) is characterized by an overall biomass turnover rate (B_j) and a concentration ratio for each particular radionuclide (CR_{ij}). Both quantities are uncertain and are therefore described by random variables. The relative variation of uptake with depth for each lifeform is described by the relative extraction rate function, $R_j(z)$. The composite transfer factor, $U_{ci}(z)$, includes the annual contribution of all lifeforms in a community and is given by:

$$U_{ci}(z) = \sum_{j=1}^{n_g} B_j CR_{ij} R_j(z)/\rho \qquad \text{(Eq. 2)}$$

where

$U_{ci}(z)$ = composite community transfer factor per year;
B_j = biomass turnover rate, in kg plant biomass/(m^2 yr);
CR_{ij} = concentration ratio, in moles per kg plant biomass/moles per kg soil;
$R_j(z)$ = relative extraction by plant roots per m length of roots in 1/m; and
ρ = mass density of soil, in kg/m^3.

$R_j(z)$ characterizes the long-term average uptake by roots of the plants in each lifeform as a function of depth z. $R_j(z)$ is designed to reflect the aggregate behavior of all individual plants in each lifeform that will be present at a given RWMS during the relevant period of performance. $R_j(z)$ is also uncertain and is represented as a random variable in the modeling of plant uptake. The modeling of $R_j(z)$ is detailed in Chapter 4.0, following the introduction below. Chapters 5.0 and 6.0 describe the modeling of CR_{ij} and B_j, respectively. Figure 7 illustrates the steps involved in simulating plant uptake, given this numerical model, and can be referenced as support to the information in Chapters 4.0 through 6.0.

3.3.1 Relative Extraction, $R_j(z)$

The function R_j describes uptake behavior of the population of individual plants in each lifeform and would ideally be calculated from the relative extraction functions for the individual plants, R_{Ijk}:

$$R_j(z) = \frac{\sum_{k=1}^{n_I} R_{Ijk}(z)}{n_I} \qquad \text{(Eq. 3)}$$

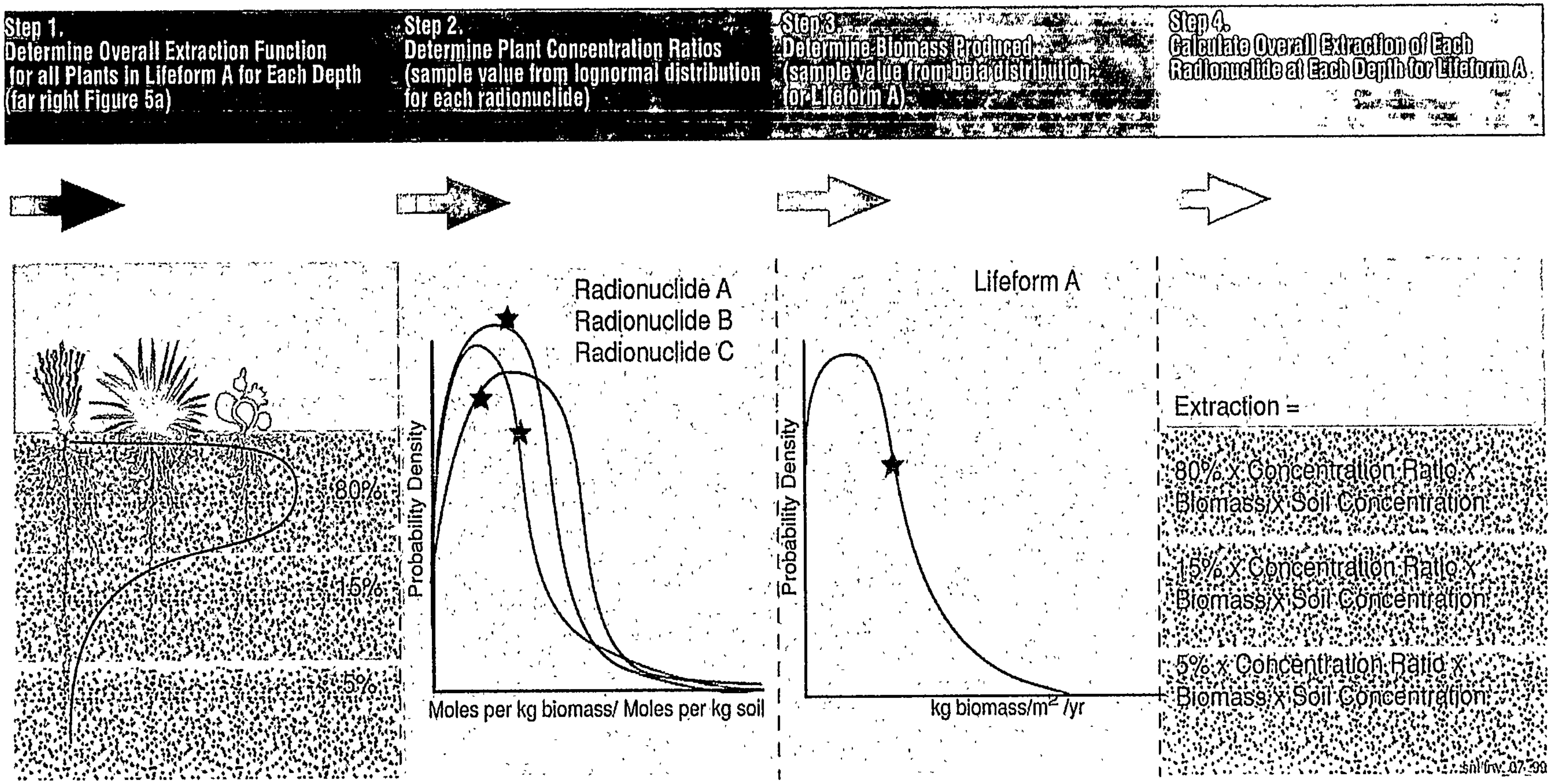

Figure 7
Simulation Example
(repeat for many individuals)

where n_I is the number of individual plants in the community. Instead, $R_j(z)$ is estimated from measurements of the maximum observed root length for a number of individual plants that have been grouped into lifeforms by species. Each individual plant is characterized by its maximum root length l_{max}. $R_j(z)$ for each lifeform can be calculated as a weighted sum over the possible values of the maximum rooting length:

$$R_j(z) = \int_{l_{\max}=0}^{\infty} X_j(l_{\max}) R_{Lj}(z; l_{\max}) dl_{\max} \qquad \text{(Eq. 4)}$$

where

$X_j(l_{max})dl_{max}$ = fraction of individual plants in group j with a maximum root length of l_{max}, unitless; and

$R_{Lj}(z;l_{max})$ = relative extraction function for individual plants having a maximum root length of l_{max}, 1/m.

In summary, $R_j(z)$ models the relative uptake of each lifeform group as a function of the maximum root length (l_{max}) and the relative extraction of individual plants within each lifeform group.

3.3.2 $X_j(l_{max})$

The function $X_j(l_{max})$ describes the relative frequency of maximum root length for individuals in each lifeform group. This function can be directly estimated from data on root lengths, as well as confidence limits for the fitted parameters of this function which capture the uncertainty in the properties of the population given the available data on root lengths. This section first describes the data compilation process for estimating l_{max}, followed by a specific discussion of the development of l_{max}.

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4.0 Relative Extraction by Roots

4.1 Overview

Roots are a dynamic component of the soil environment, actively seeking soil water resources and drawing those resources to them (Everett et al. 1977). In the arid southwest, the depth of infiltration tends to set the lower limit of rooting depths for all but exploratory roots, constraining most roots to near-surface layers receiving moisture from precipitation. Site-specific data support the assumption that most root depths are limited by the depth of infiltration but that roots. can and will grow deeper in areas with increased effective moisture (Wallace and Romney 1976 and Wallace et al. 1980).

While roots tend to concentrate in areas with high available water, exploratory roots can extend into relatively dry areas of the soil. The depth and extent of root exploration is primarily determined genetically (Foxx et al. 1984a). For example, some plants have very shallow root systems, regardless of soil conditions at greater depths; other plants send roots to great depths, even though the soil at these depths may be considerably drier. Additionally, decreases in available soil water around roots may be compensated for by root growth (Weaver and Clements 1938 and Noy-Meir 1973). The presence of shrub and tree roots at great depths is often due to the ability of these long-lived plants to maintain extensive root systems both within soil and within and along subsurface heterogeneities, such as cracks and fissures, following (and creating) subsurface flowpaths for water. Thus, it is important to evaluate maximum root depth, as well as the depth of infiltration, when assessing the potential impact of plants on a waste site. This is particularly important at the NTS, as plants from arid environments or those from environments with a long dry season have the deepest rooting habits of all (Canadell et al. 1996). Water extracted by roots after precipitation events comes from the near-surface where root density is highest. As these layers dry there is a progressive shift towards using deeper water, allowing plants to keep stomata open and extend growth far into the dry season (Canadell et al. 1996).

All plants actively modify their root environment to some degree. One impressive example of this comes from big sagebrush (*Artemisia tridentata*), a shrub broadly distributed throughout the NTS but most common in the Transitional and Great Basin Deserts. Big sagebrush has been shown to act as a "hydraulic lift," actually increasing water content in dry soil layers by releasing water "mined" from wetter soil layers (Caldwell and Richards 1989). The water is released at night and during periods of low transpiration and is reabsorbed when transpiration resumes. The root system is considered "self-irrigating." Though the extent of the hydraulic lift phenomenon across plant species is unknown, the impact of this single species appears to improve transpiration on a landscape scale, dramatically influencing the partitioning of water between evapotranspiration and subsurface flow in arid areas (Caldwell and Richards 1989). Though this degree of root activity is not accounted for in this model, this information is provided as an example of the dynamic and active nature of root uptake. This example also emphasizes the possibility that exploratory roots will find and exploit soil layers with available soil moisture, often found in the deeper vadose zones.

All reported root lengths (lateral and horizontal) are important to this plant uptake model for the development of root length distributions. For all plants, a maximum rooting depth exists, which may be a function of plant type, size, age, environmental conditions, and site hydrology. This maximum is estimated from existing data, as described in Sections 4.2 through 4.4. The modeling of relative uptake by roots is described in Section 4.5. This portion of the uptake model is illustrated as Step One in Figure 7.

4.2 Assumptions and Uncertainties

The following assumptions were made in compiling data for estimating maximum root depth:

1. Lateral root length serves as an appropriate analogue for vertical root length and vice versa. The distinction of lateral and vertical roots is often one of origin or form, not of function (T. Foxx, pers. comm, Weaver and Clements 1938, and Canadell et al. 1996). While some roots may tend towards lateral orientation, in most plants these roots can and will grow vertically, following cracks, fissures, textural boundaries and discontinuities, and moisture zones in the soil. In other words, given similar conditions with depth, roots that grow laterally could extend vertically. Although average, long-term, near-surface conditions are not mirrored vertically, using data for lateral roots growing in more favorable conditions captures more of the uncertainty in how deep roots might grow in the future (either because of changes in moisture infiltration or because of root exploration into deeper soil layers);

2. Maximum reported root lengths from appropriate analogue communities, including more mesic locations with potentially deeper-rooted individuals, provide an expected physical limit to rooting depths at the NTS. These analogue sites are from the southwest U.S.;

3. Taxonomic similarities translate into physiologic similarities and data for one species can be applied to related species. Individual plants with root length data had to match NTS species, at the very least, at the taxonomic level of genus; and

4. Root lengths are best described by continuous, rather than discrete, distributions.

4.3 Data Compilation

Data were retrieved from a database of plant rooting lengths of native southwestern and western arid and semi-arid plants compiled by T. Foxx (Los Alamos National Laboratory) from an extensive literature search of publications reporting root lengths, as well as original data derived from field excavations conducted by Foxx and others in northern New Mexico (Tierney and Foxx 1987). A number of reports document these database findings (Foxx et al. 1984a and 1984b, and Tierney and Foxx 1987). Appendix A includes the root length data by species and lifeform.

Each root length reported in the literature is a separate record in the database; some citations contain numerous records. The values in the database for root lengths are the maximum values reported in the given citation, and as such, can only be considered maximum **observed** rooting lengths, not necessarily maximum **possible** rooting lengths obtained by the plants. For example, if an excavation was performed only to a depth of 2 m and roots were found at that depth, then the value recorded in the database is 2 m. For this reason, there might by a bias to shallow roots in the data sets compiled, as "maximum observed" samples may truncate the actual distribution of "maximum obtained." Lateral root length data were also included in the data compilation in order to derive distributions of maximum root length, serving to compensate for the potential bias created by using maximum observed root lengths.

4.4 Variation in l_{max}

Estimating maximum root length given the dynamic nature of root growth requires simplifications for modeling. As presented previously, for each lifeform there are a number of observations of maximum root length for individual members of species in that lifeform. Each observation represents a lower bound on the length of the longest root for the individual, as described above. However, these data do not completely define the variability in the maximum root length for individuals of the lifeform because the number of observations is limited. For each lifeform, there are enough observations to estimate this distribution (with some uncertainty about the distribution remaining). This uncertainty can be described by assuming a functional form for the maximum root length distribution, as described below.

An exponential model for the variability of maximum root length has been assumed for several reasons. An exponential distribution is commonly used to model biological processes. Assuming that the length of the longest root grows at a more or less constant rate over a plant's lifetime, and that rate is characteristic of the lifeform, then the distribution of root lengths should follow the distribution of plant lifetimes. Theoretically, the waiting time before the first occurrence of events governed by a Poisson process has an exponential distribution, such as the waiting time until death. Practically, the distribution is characterized by a single parameter, corresponding to the expected value of root length for a plant. This makes it possible to develop confidence limits for this parameter using only a single observation, though this is never required for the data presented here, since there are multiple observations for each lifeform. Under this assumption of an exponential distribution of maximum root lengths:

$$X_j\,(l_{\max}) = \frac{1}{L_j} e^{-l_{\max}/L_j} \qquad \text{(Eq. 5)}$$

where L_j is the mean value of the maximum root length for individuals in lifeform group j, in meters. This average maximum has been described by Canadell et al. (1996) as the measurement most relevant to ecosystem functioning for resource utilization by plants.

Again, although this value is uncertain, a distribution describing the uncertainty in the mean value can be developed from the root length observations in the database. Each lifeform consists of species that behave similarly, exploit similar ecological niches, and is likely to be dominated by one or two species from the group of species in that lifeform. We are uncertain as to which species might dominate a given lifeform in a particular community, and there is no reasonable way of reducing this uncertainty. Assuming that environmental factors shape the distribution of maximum root lengths and that this process is similar for all members of a lifeform, the observed root lengths in the database for a given lifeform are *all* relevant for estimating root lengths for individual plants in an actual community, even though that community may be dominated by a single species from the lifeform. Thus, species-specific information in the database determines only lifeform group classification. Average maximum root lengths, as well as other data descriptors, are given in Table 1.

For each lifeform, the basic statistical parameters are nearly identical for the current and future data sets. This is likely because "future" data sets are inclusive of all the data in "current" data sets. This inclusion follows the assumption that future communities are an admixture of those species found currently in the low elevation shrublands and species growing in areas with higher effective moisture that are expected to encroach on the current shrublands if and when such moisture conditions exist.

Table 1
Statistical Parameters for Maximum Root Length Data Sets (in cm)

Parameter	Annual		Perennial		Shrub		Tree
	current	future	current	future	current	future	future
number of observations	17	23	90	196	43	71	64
average	35	39	109	106	293	262	485
median	13	13	88	85	180	183	287
standard deviation	49	49	107	95	312	259	590
minimum	2	2	2	2	35	35	20
maximum	162	162	823	823	1,737	1,737	3,000
Mann-Whitney U test p-value[a]	0.83		0.82		0.93		not performed

[a]Significance determined at a p-value ≤ 0.05. All values greater than 0.05 are non-significant.

The data sets of maximum root length for current and future conditions were tested for differences with a Mann-Whitney U test. Strictly speaking, the assumption of independence required for the Mann-Whitney test is violated. The samples representing current and future conditions are not independent because the samples representing future conditions contain the same species as are currently found at the site. The relevant question for the test is whether the influence of the added species is sufficient to warrant defining a separate distribution for future conditions. This decision cannot be based on the added species alone, although such a comparison would satisfy the assumption of independence. The fact that future communities would include the same species, and simply the same "types" of species, as the current community is an important consideration in evaluating the need for separate current and future distributions. The Mann-Whitney test is therefore used as an indication of similarity in forming judgement about the value of defining separate distributions, but its results were not intended to provide proof at some specified level of significance. In no test were statistically significant differences detected (Table 1). Thus, there appears to be no compelling reason to separate the root length data of current and future species of a lifeform. Appropriate statistical parameters for the maximum root length data for current and future conditions are those labeled "future" in Table 1. Box-and- whiskers plots of the data are shown in Figure 8. The median is shown as a line which falls somewhere within the range where 50 percent of the data fall; this 50 percent is called the interquartile range (IQR) and is shown as a box. Values exceeding 1.5 * IQR are defined as outliers. Extremes are values exceeding 3.0 * IQR. The only practical difference between current and future communities is the addition of "trees" as a lifeform category.

Certain features of the data sets are consistent with assumptions being made about the various lifeform groups. First, the average maximum root length for each lifeform should parallel the relative size and longevity of the lifeforms. Size and length of lifetime for the lifeforms can be

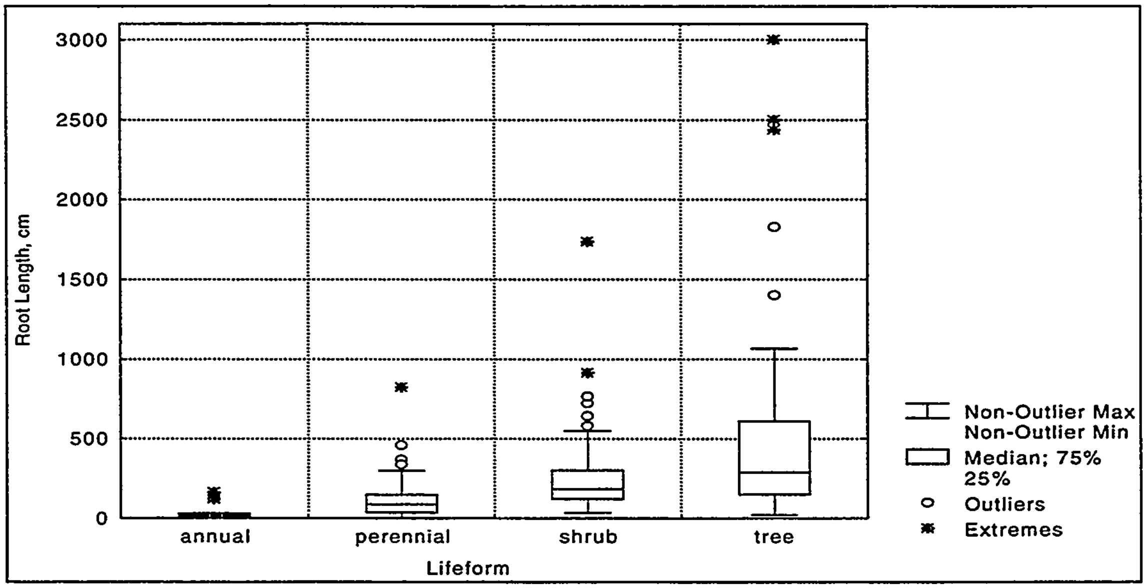

Figure 8
Box-and-Whiskers Plots of Maximum Observed Root Length, by Lifeform

ordered as follows: annuals < perennials < shrubs < trees. The average maximum root lengths follow this pattern, with annuals having the shortest average maximum root length (39 cm) and trees having the largest average maximum root length (485 cm). Second, the measured maximum root lengths follow this pattern, with annuals having the shortest (162 cm) and trees with the longest at 3,000 cm. Lastly, the statistics of the lifeform groups are also generally consistent with the assumption of an exponential distribution for maximum root length. An analysis of this final point is included in Appendix A (Section A.1).

The relative frequencies of l_{max}, assuming the exponential functional form as estimated from the mean values for each lifeform, are shown in Figure 9. The shorter the average maximum root length, the higher the relative frequency at small values of l_{max}. In other words, the longer the average maximum root length, the lower the expectation of a root terminating in shallow soil depths.

A detailed analysis of individual species variability versus lifeform variability is provided in Appendix A (Section A.2). In summary, the analysis suggests there are similar uncertainty distributions whether placing confidence limits about the lifeform average or using the variability among the species for all the lifeforms. That the variability within and among species is consistent with the overall population variability for each lifeform precludes the necessity to distinguish among species within a lifeform to determine l_{max}.

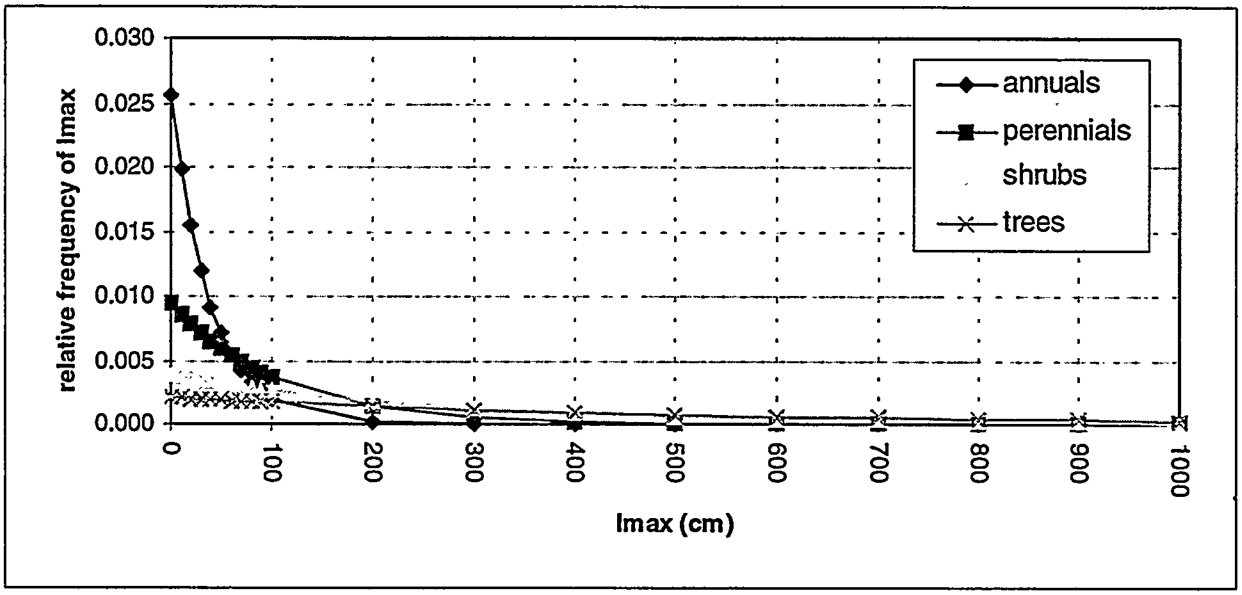

Figure 9
Relative Frequency of l_{max} [X_j (l_{max})] as a Function of l_{max}

4.5 Relative Extraction Rate, $R_j(z)$

Soil microsite conditions vary considerably across space and through time, producing variations in root activity. Local soil conditions influence root activity throughout a plant's root system. The actual contribution by a given portion of the root system to biomass depends largely on resource availability within a soil interval and the extraction that occurs by roots within that interval. The relative extraction function for an individual plant is non-zero between the land surface and the maximum root depth and varies in some unknown way within this interval. The model of extraction presented here assumes that the variations in extraction among individual plants of the same lifeform is due to the variation in the maximum rooting length over those individuals: the shape of the relative extraction function scales with maximum rooting length. Here, maximum root depth (l_{max}) is modeled and uptake is scaled as a function of l_{max} using a beta function bound by the land surface and l_{max}. The shape of the beta curve is treated as uncertain and is varied by altering the parameters of the beta function, as detailed below.

The beta "distribution" function is a good choice to represent the spatial variations in relative extraction rate because it is limited, normalized (like the relative extraction), and can be warped into a wide variety of shapes reflecting the uncertainty about the behavior of individual plants. "Distribution" in this sense does not describe a probability density, but rather the variation of extraction rates with depth.

While not all possible relative extraction functions (e.g., multi-modal functions) can be approximated by the beta function, it can represent preferential extraction from shallow roots. Thus, for each individual plant we assume that $R_j(z)$ is described by a beta function defined between the land surface and the maximum observed root length. Additionally, whatever the parameters of the beta function are, they are assumed to be the same for all individuals of the lifeform. Uncertainty in $R_j(z)$ is represented by assigning probability distributions to the parameters of this beta function.

Extraction throughout the soil profile is systematically described by a beta function between a depth of 0 and l_{max}:

$$R_{Lj}(z;l_{\max}) = Cz^{A}(l_{\max}-z)^{B} \quad with \quad C = \frac{1}{\int_0^{l_{\max}} Z^{A}\left(l_{\max}-z\right)^{B} dz} \qquad \text{(Eq. 6)}$$

Values of parameters A and B are provided so that the relative extraction rate function allows for varying degrees of decreasing extraction with depth. The beta functions plotted in Figure 10 illustrate the way that extraction is modeled for different choices of A and B.

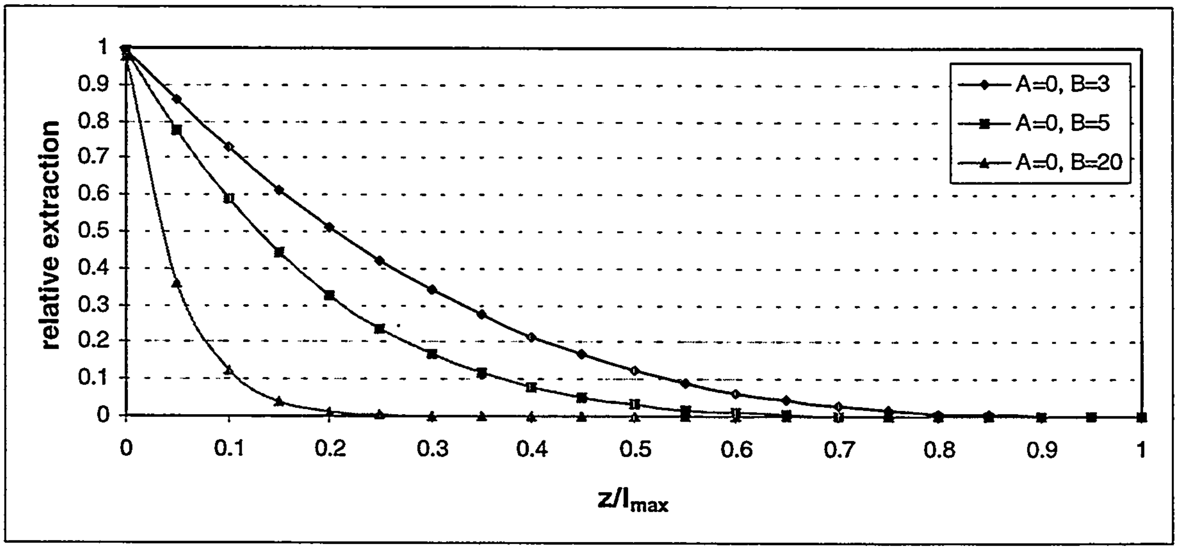

Figure 10

Beta Functions of Relative Extraction with Depth, Normalized to the Longest Observed Root Depth (z/l_{max})

Holding A = 0 ensures that the maximum extraction rate occurs near the surface. Increasing B tends to shift the "mass" of the distribution toward the surface (x = 0); that is, extraction by near-surface roots exceeds that by deeper roots. At approximately B = 20, large increases in B are required to shift the position of the relative extraction curve, sometimes only slightly. As B falls below 3, the shape of the curve begins to "flatten," meaning that relative extraction is nearly uniform across depth. Given that there is little information on the specific mechanisms responsible for differential extraction with depth, the following sampling protocol is proposed:

- All beta functions describing relative extraction with depth are considered equally probable and thus, evenly-weighted sampling among the distributions should occur;

- Parameter A should be held constant at zero to maximize relative extraction near the surface; and

- Parameter B should range between 3 and 20 to model classes of extraction functions that provide for decreasing amounts of extraction with depth.

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5.0 Concentration Ratios

5.1 Overview

For plants growing in contaminated soil, the complex process of radionuclide uptake from the soil to plant tissue is simplified into a parameter called the concentration ratio (CR), and as defined in Equations 1 and 2 is described as follows:

$$CR_{ij} = \frac{pCi\ activity\ per\ kg\ dry\ above\text{-}ground\ biomass}{pCi\ activity\ per\ kg\ dry\ soil} \qquad \text{(Eq. 8)}$$

The units of radionuclide activity are not always in pCi. However, as long as the units of activity for the plant and the soil are the same, the ratio of plant to soil concentration is preserved and can be used to compare data from different sources. CR_{ij} is defined as zero when the soil concentration is zero.

One limitation of this CR model is that it is not necessarily applicable to an infinite range in plant and soil concentrations, as is predicted by the linear model. There will always be some concentration above which the uptake rate begins to decline with increasing soil concentrations, which would be observed as an asymptotic curve when plotting plant concentrations against soil concentrations. However, these limits are rarely observed experimentally, nor do they appear to apply to the CR data compiled here. Thus, a linear relationship between plant and soil concentrations is assumed across the ranges of CR values complied here. Additional defense for this assumption is provided in Section 5.2.

The process of uptake is an active process, as first described in Section 3.1. Root surfaces are more than mere semi-permeable membranes that passively receive nutrients from the soil. Roots actively modify their environment, discharging chelating agents and other organic substances that enhance nutrient extraction and uptake from the soil.

As Sheppard and Evenden (1988) point out, despite the simplicity of the CR model, the processes underlying plant uptake are very complex, resulting in substantial variability in CR data. Plant uptake is the result of many different chemical, biological, and physical processes and, as such, is affected by variability in factors such as climate, weather, growth conditions, plant metabolism, plant rooting traits, soil type, soil texture, soil moisture, and soil pH, to list a few. CR distributions with several orders of magnitude difference between the minimum and maximum observed CR are not uncommon (Arkhipov et al. 1975, Dahlman et al. 1976, Whicker 1978, and Sheppard and Evenden 1988). This chapter presents CR data used to justify a CR model parameter value and the uncertainty in that model parameter value. A direct application of the available CR data to the generation of probability distribution functions (pdfs) for use with TRU waste is provided. This component of the uptake model is illustrated in Step Two of Figure 7.

5.2 Assumptions and Uncertainties

This section summarizes assumptions inherent to the CR model and identifies additional assumptions necessary for modeling plant uptake as a function of the CR.

One basic assumption of the CR model is that the plants and soil are in equilibrium. For a given species and a given radionuclide concentration in the soil, all that can be taken up by the plant has been taken up at the time the radionuclide concentrations in the soil and plant are measured. In the strictest interpretation of the CR model, two assumptions underlying that of plant and soil equilibrium are that plant and soil concentrations are linearly related and that the relationship has a zero intercept (Sheppard and Sheppard 1985 and Sheppard and Evenden 1990). As Sheppard and Evenden (1990) found, these assumptions were valid when plant and soil concentrations were averaged by element and that, despite the unique chemical behavior of each element, plant concentrations were linearly related to soil concentrations especially when the latter ranged over five orders of magnitude. Sheppard and Evenden (1990) note, however, that the true relationship of plant to soil concentrations is often difficult to demonstrate in the field, probably because the range of soil concentrations is narrow relative to the effect of other environmental sources of variability. The inclusion of environmental variables, such as soil texture and pH, reduced the variability in CR estimates only marginally (Sheppard and Evenden 1990). Without the means to quantify such variability, the assumption of a linear relationship between plant and soil concentrations must be made, and seems appropriate given the broad range of soil concentrations in many of the studies used here.

Also inherent in the CR model is the assumption that a given soil concentration results in the same equilibrium plant concentration, irrespective of the actual density of the roots in the soil. Thus, CR is a function only of root presence and soil concentration. For modeling CR, this eliminates the need to know root density to calculate plant concentration; the only rooting parameter of importance is the probability that a root is present at a given depth. Uncertainty in uptake as a function of depth and the change in density of roots with depth is treated separately from CR; this uncertainty is treated with R_j (l_{max}).

Another assumption of the CR model is that the radionuclide of interest can be grouped by element. Often this was required due to a lack of sufficiently-sized data sets to determine if there were statistical differences (or similarities) among isotopes. Sheppard and Evenden (1988) provide support for this approach, as they found the variability among isotopes to be a minor source of the variation in uptake factors. Thus, retaining isotopic specificity narrows the data sets without providing a concomitant narrowing of uncertainty.

The CR model assumes that all roots extract radionuclides from the soil with equal efficiency and contribute in equal shares to the production of plant biomass. The uncertainty in the contribution of different roots to plant uptake is addressed explicitly in the models of relative extraction as presented in Chapter 4.0.

One final assumption made in modeling radionuclide uptake through the incorporation of radionuclides into plant biomass is that release to the environment via plants occurs only through above-ground plant biomass production and turnover.

5.3 Data Compilation

CR data were compiled from a literature search for native, desert plants. Five criteria were used to screen the CR data:

1. The plant species had to be from arid or semi-arid locations in the western and southwestern United States. For most of the studies used, the plants were either identical to species native to the NTS, or else they were from the same genera as plants native to the NTS.

2. Only CR data for above-ground plant parts were used. Roots are not part of the above-ground biomass that is shed from the plants and thus do not contribute to soil contamination via off-site transport and surface redeposition. Additionally, root CR data are often suspect of surface contamination. Failure to take appropriate measures to wash contaminated soil from the root surfaces can result in gross overestimations of the CR. In most studies, it was impossible to verify that such precautions were taken and as a result, it was deemed best to exclude all root CR data.

3. Only data from plant samples that were washed of potential surficial contamination were considered here, as non-washed samples can lead to erroneously high CR values and fail to adequately represent radionuclide uptake through plant roots. Washing is not always 100 percent effective at removing external foliar contamination and does not completely ensure that uptake through foliar deposition

is eliminated as a pathway for radionuclides into plant biomass. This criterion eliminates potential surface contamination, which should not be confused with foliar contamination via root uptake from the soil. Foliar deposition from contaminated dust and airborne particles is an issue for other PA transport models, and data suspected of such "error" were excluded.

4. Only data reported as a function of the ratio of the plant sample's dry weight to the soil sample's dry weight were used. This was deemed important in reducing some of the variability in the CR data. Reducing this variability, which is difficult to control, has led most researchers to report CR data in units of plant and soil dry weight (Sheppard and Evenden 1988).

5. Because foraging animals are assumed to feed on all aboveground plant parts, no distinction among plant parts was made. In other words, there was no justification to exclude CR data for some plant parts, while including CR data from other plant parts. Accordingly, all CR data for above-ground vegetation were screened for inclusion in the data sets.

6. The following key elements are considered in this report: actinium (Ac), americium (Am), cesium (Cs), chlorine (Cl), lead (Pb), neptunium (Np), protactinium (Pa), plutonium (Pu), radium (Ra), strontium (Sr), technetium (Tc), thorium (Th), and uranium (U).

Building data sets for some of the radionuclides required a unique approach not fully addressed by the screening criteria. These "special cases" are detailed below.

1. Lacking CR data for ^{227}Ac , ^{241}Am was used as an analogue for ^{227}Ac. This is in accordance to Grogan's (1985) assumption that the two radionuclides behave similarly because they share a dominant oxidation state (+3). Their chemical similarities and the fact that both are actinide elements are considered sufficient reasons to use Am as an analogue for Ac.

2. CR data for ^{237}Np were compiled as an analogue for ^{231}Pa data-again, due to a lack of data and in keeping with assumptions of chemical similarity between the radionuclides topes as detailed by Grogan (1985).

3. Few reliable studies of Tc uptake exist (Hoffman et al. 1980, Baes et al. 1984, and Grogan 1985). Short-term studies using very high concentrations yielded CR values that seemed to be limited only by the availability of Tc and its concentration in the soil (Grogan 1985). Baes et al. (1984) raised many concerns over these experiments, concluding that "the application of short-term pot studies to long-term assessments is clearly inappropriate for technetium." Baes et al. (1984) provide CR values of 1.5 and 9.5 based on field measurements of long-term Tc uptake; the two values represent different above-ground plant parts. Similarly, Grogan (1985) used results from a long-term field study (Eriksson 1983), predicting that under continuous releases of small amounts of Tc, CR values should be of the same order of magnitude as those for Cs. The assumption here is not that Cs is an appropriate physiological analogue for Tc, but that Cs is an appropriate mathematical analogue for Tc based on long-term field studies. Combining the conclusions from the two long-term studies, 9.5 and 1.5 were added to the uptake data for Cs to estimate Tc CR values.

4. The final "special case" element is chlorine. Very little literature exists on chlorine uptake by plants; even less information is available for actually calculating CR values; and no data were found for native plant species. What is known is that Cl is an essential micronutrient for plants and most plants absorb 10 to 100 times the amount of Cl that they require, a process called luxury consumption (Salisbury and Ross 1985). Evidence presented below indicates that CR values for Cl may be a function of the soil concentration of this element. This is accounted for in the PA model by determining an upper limit (conservative CR) for plant uptake of Cl based on toxicity data (Kabata-Pendias and Pendias 1992), derived as follows:

   Given an average concentration of Cl found in plants at an upper threshold of tolerance of 2,700 mg Cl/kg plant dry weight and an average concentration of Cl in the soil at which toxicity is observed of 2,003 mg Cl/kg soil solution, the CR value at this upper limit of tolerance is 1.35 (2,700/2,003). However, this is an order of magnitude less than the CR value of 70 given by Baes et al. (1984), suggesting that the CR may not be constant over a wide range of soil Cl concentrations. Until more data become available, it is suggested that the higher CR value for Cl be used pending additional studies, particularly with desert plants because they are among those species most tolerant of the high levels of Cl typical of many arid soils.

CR data for the different lifeform groups were combined into a single data set for two reasons. First, there are often too few data to reliably determine differences among the lifeforms. Secondly, and more importantly, two studies demonstrated no significant differences among CR values for native shrubs, grasses, and forbs (Ibrahim and Whicker 1987 and Ibrahim and Whicker 1988a). Appendix B includes the CR data used for creating pdfs and modeling CR.

There are two defensible ways of treating uncertainty in small or nonexistent data sets: (1) use uptake data for other elements and retain native plant species specificity, or (2) use uptake data for other species (non-native) and retain element specificity.

The former option is chosen here and a "generic" data set made up of all the uptake data is provided for use when data are scarce or nonexistent for an element. Defense for this is based on recent research that suggests CR values for native plants differ dramatically from those for nonnative (i.e., agricultural) species (Sheppard and Evenden 1997). Using a large database of CR values for Cs, Sheppard and Evenden (1997) show that even the most generous (broad) distribution choices based on agricultural CR values capture no more than 66 percent of the CR values for native species. Relatively high values for native species lie outside the modeled distributions. This evidence demonstrates that data sets for native species built from data for agricultural species cannot adequately describe the variability in native plant uptake, as they would likely underestimate radionuclide uptake by native plants.

Another reason to retain species specificity comes from the Sheppard and Evenden (1997) study, which looked closely at variation in transfer factors for more elements than just Cs. In their conclusions, they state that "CR values are related to site-specific conditions, but there is still a large amount of variability." They found that the most significant amount of variation could be explained by the plant species for which data were taken. Other variables, such as soil type, and particularly continuous variables, such as soil pH and organic matter content, significantly affected CR, though all had numerically small correlation coefficients. Their results clearly show that there is little added value to screening data for site specificity beyond the plant species expected to inhabit the site.

5.4 Statistical Analyses and Results

As with the other parameters used to estimate plant uptake, the model requires CR distributions that adequately describe the uncertainty associated with a single, lumped parameter which represents a value for a broad spatial area, a long time period, and a diverse mix of plant species. The CR data sets compiled are collections of measurements taken at relatively small spatial and temporal scales from studies where some factors affecting radionuclide uptake were experimentally controlled, other factors were experimentally varied, and still others were not controlled.

A lognormal distribution is suggested by Sheppard and Evenden (1988) to help solve for the uncertainty in CR data because CR values result from the product of several variables. This conclusion is consistent across many different uptake studies (Gilbert and Simpson 1985, Sheppard and Evenden 1988, Sheppard and Evenden 1990, and Murphy and Tuckfield 1992). Accordingly, parameters of the lognormal distribution of each data set were calculated from the measured data. Lacking CR values from the population of interest (lumped parameters for a specific disposal area), this is a reasonable next-best approach.

A perfect match of the collected data and the assumed distribution(s) is not a necessary requirement for data parameterization. Nonetheless, "goodness-of-fit" measures (Shapiro-Wilk and Lilliefors normality tests; see Appendix D for details of the analyses) were used to evaluate the lognormality assumption for each data set. The results of the distribution tests performed on the log-transformed CR data for the current shrubland and potential future communities are presented in Appendix B (Tables B-2 and B-3).

The statistical tests show that it is not unreasonable to assume a lognormal distribution for all the data sets, with the exception of the generic data sets. These two data sets were also tested for normality and both data sets failed. However, histograms of the generic data sets overlaid by the pdfs, assuming lognormality, show that the resulting pdfs appropriately describe the data. An example of this is provided in Figure 11 for the generic CR data set for potential future species. For visual clarity, the x-axis is truncated at CR = 5.0. Thus, lognormal pdfs and statistical parameters based on the assumption of lognormality were generated for the generic data sets, even though they failed the lognormal distribution tests.

Statistical parameters for each data set are presented in Tables 2 and 3. The mean and the standard deviation were determined from the underlying normal distribution of each data set, while the upper and lower quantiles were generated assuming lognormal distributions. Data sets with less than ten observations were deemed insufficient for parameterization.

5.5 Discussion

The CR data show considerable variability in CR values from element to element. Particularly striking is that, within a data set, there can be values several orders of magnitude apart. For some elements, this variability is most likely a statistical consequence of the small size of the data set. While larger data sets might have enough data points to indicate that very high CR values are outliers that do not conform to assumptions of lognormality, this cannot be determined reliably for small data sets. Lacking a statistical basis to exclude high values from the analysis

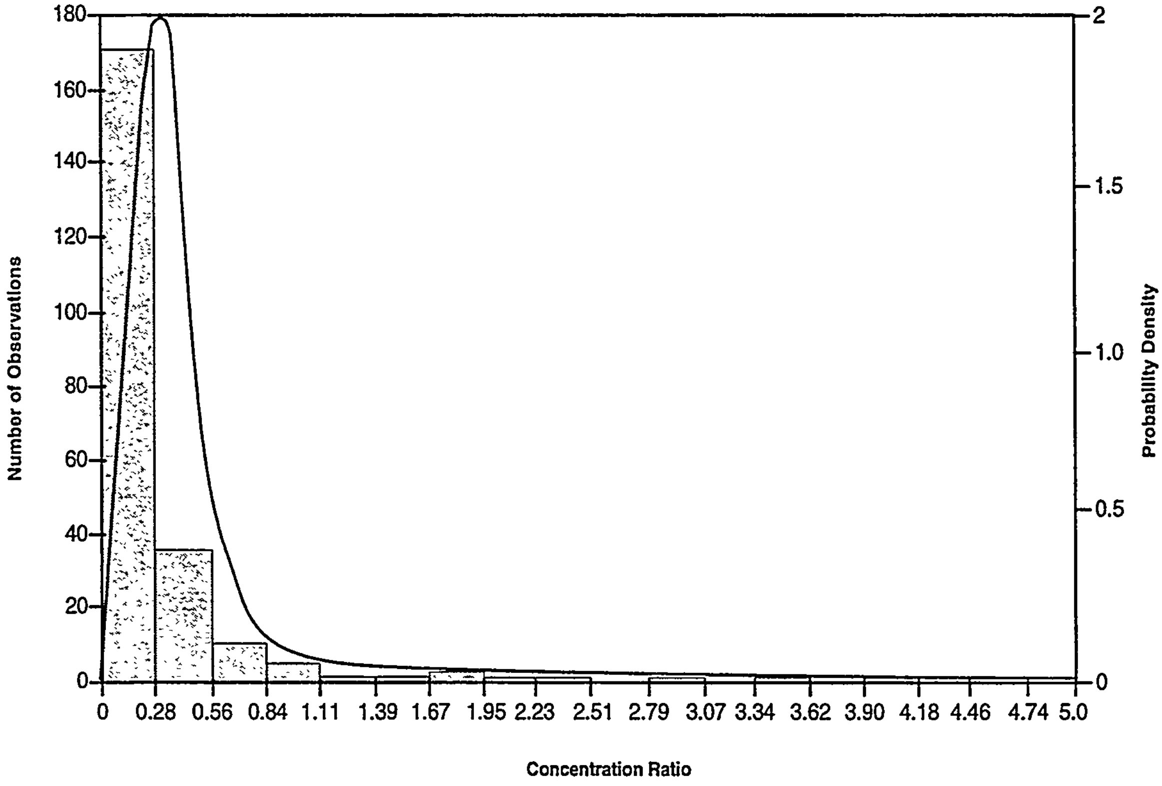

Figure 11

Histogram of All CR Values for Potential Future Species, Overlain by the Lognormal PDF Representing These Data

for these small data sets, all data were included. This is also a more conservative approach, as excluding high end "deviations" would skew the distributions to smaller values.

Nonuniform distributions of radionuclides in the soil also contribute to the tremendous variability in CR data. As Kinnear et al. (1981) discovered, CR values can range more than an order of magnitude with even the most careful attempt to obtain a uniform soil mixture. This nonuniformity is compounded by a number of other factors in the field, producing large ranges like those found here. To some degree, including all CR values that fit the qualifying criteria shows that, though the distribution of radionuclides in the soil is modeled as uniform, it really is not. As a result, the CR values used here incorporate actual variability in uptake by mirroring insitu conditions.

Table 2

Statistical Parameters for CR Data, Current Shrubland Conditions

Radionuclide Element	Parameter						
	number of observations	minimum	maximum	mean[a]	standard deviation[a]	0.001 quantile[b]	0.999 quantile[b]
Am (analogue for Ac)	12	6.0E-05	1.7E-02	2.2E-03	4.7E-03	1.7E-05	5.4E-02
Cs[c]	1	-----	-----	5.4E-01	-----	-----	-----
Np (analogue for Pa)	12	7.0E-03	2.8E-01	1.1E-01	1.2E-01	5.2E-03	1.1E+00
Pb	20	1.4E-03	9.9E-01	3.2E-01	3.7E-01	1.3E-02	3.6E+00
Pu	13	1.4E-05	8.6E-04	1.6E-04	2.4E-04	1.5E-06	2.5E-03
Ra	30	4.7E-03	7.4E-01	1.7E-01	1.7E-01	9.4E-03	1.6E+00
Sr[c]	2	4.2E+00	6.2E+01	3.3E+01	-----	-----	-----
Tc[c]	3	5.4E-02	9.5E+00	3.7E+00	5.1E+00	-----	-----
Th	24	1.2E-02	1.1E+01	1.4E+00	3.1E+00	8.5E-03	3.5E+01
U	24	4.3E-03	1.9E+00	2.9E-01	4.8E-01	4.5E-03	5.1E+00
all data (generic)	140	1.4E-05	6.2E+01	9.2E-01	5.4E+00	4.5E-04	5.3E+01

[a] This parameter is from the underlying normal distribution.
[b] This parameter is from the data's lognormal pdf.
[c] There are insufficient data to determine some distribution parameters.

Table 3

Statistical Parameters for CR Data, Potential Future Conditions

Radionuclide Element	Parameter						
	number of observations	minimum	maximum	mean[a]	standard deviation[a]	0.001 quantile[b]	0.999 quantile[b]
Am (analogue for Ac)	14	5.0E-05	1.7E-02	1.9E-03	4.4E-03	1.2E-05	5.0E-01
Cs	13	1.2E-02	1.3E+00	4.8E-01	3.8E-01	4.2E-02	3.3E+00
Np (analogue for Pa)	12	7.0E-03	2.8E-01	1.1E-01	1.2E-01	5.2E-03	1.1E+00
Pb	26	1.4E-03	3.0E+00	4.3E-01	6.3E-01	8.9E-03	6.6E+00
Pu	15	8.0E-06	8.6E-04	1.7E-04	2.4E-04	3.9E-06	2.5E-03
Ra	41	2.2E-03	7.4E-01	1.3E-01	1.7E-01	3.9E-02	1.7E+00
Sr[c]	2	4.2E+00	6.2E+01	3.3E+01	-----	-----	-----
Tc	15	1.2E-02	9.5E+00	1.2E+00	2.4E+00	9.5E-03	2.7E+01
Th	58	3.1E-05	1.1E+01	6.9E-01	2.1E+00	2.1E-03	2.4E+01
U	56	7.0E-04	3.5E+00	3.1E-01	6.3E-01	2.7E-03	7.1E+00
all data (generic)	239	8.0E-06	6.2E+01	6.6E-01	4.2E+00	2.8E-04	3.9E+01

[a] This parameter is from the underlying normal distribution.
[b] This parameter is from the data's lognormal pdf.
[c] There are insufficient data to determine some distribution parameters.

While there should be reasonable explanations for CR variability, there is, unfortunately, often very little supporting documentation within a given study to provide such explanations or determine which factors might be influencing the variability in CR values. Lacking the necessary information to rigorously evaluate such variability, the approach being taken is that variability is an inherent feature of CR data, reflected in the data sets compiled to predict CR values.

Data specificity, due to detailed screening criteria, serves to lower the variability within a given data set (Sheppard and Evenden 1997). In a study of CR distributions by Sheppard and Evenden (1997), the broadest, fully generic data sets for elements have geometric standard deviations (GSD) that range from 2.4 to 16. The narrowest data sets of site- and species-specific data have GSDs that range from 1.1 to 3.7. For the data sets compiled here, the variability within each data set, as measured by the GSD, never exceeds 1.34 (Appendix B, Table B-4). Thus, all data sets are well within the range of variability observed by Sheppard and Evenden (1997). One conclusion is that, even though the absolute values of uptake for native species may seem high—often exceeding those found for agricultural species—the actual variability within the data sets is not excessive.

Concentration ratios for native plants are not necessarily suspect simply because they may exceed those for agricultural species. In fact, efforts to remediate contaminated soil by plants within the southwest often capitalize on the ability of native plants to bioaccumulate (via high uptake rates) soil contaminants, especially metals. The next section provides a more detailed comparison of native and agricultural plant CR values.

There are partial explanations for some of the highest CR values (e.g., Th and Sr). In the case of Th, the high values were for ^{230}Th uptake by plants growing at the edge of a contaminated tailings impoundment (Ibrahim et al. 1982 and Ibrahim and Whicker 1988a). It is possible that acidity and wet conditions enhanced the solubility, availability, and thus, uptake, of ^{230}Th. The authors also suggest that foliar deposition of ^{230}Th in pond water spray and subsequent foliar absorption may have been another uptake mechanism at the impoundment edge. However, evidence for foliar absorption of ^{230}Th is weak, as there is no evidence for this mechanism with other radionuclides in the study. Additionally, because the CR values reported for ^{230}Th fall far below what the authors expected due to external plant contamination, the high CR values for Th were assumed to be due to root uptake and were retained in the analysis.

The high Sr values were from shrubs growing on a former liquid waste disposal site (Fresquez et al. 1995). One plant in the study had Sr levels 300,000 times higher than the control plant. The validity of the high Sr values goes unquestioned by the authors who maintain that high Sr uptake is a reflection of its high mobility and its chemical similarity to Ca, which causes Sr to be readily taken up by plants. This chemical similarity to Ca has also been invoked as an explanation for high Sr uptake values reported for other plants (Evans and Dekker 1965).

The data do tend to follow the expected uptake pattern of actinides, which indicate CRs are often ordered as follows: Np>Am~U~Cm>Pu.

A consequence of using lognormal distributions is the potential for very high upper CR values. In these data sets, this is most obvious when the 0.999 quantile exceeds the measured maximum, sometimes by an order of magnitude. The likelihood of these high quantiles causing problems in the overestimation of uptake can be investigated on an individual basis.

By using the CR model of uptake, we are attempting to make generic what is actually plant-, element-, and site-specific. Whatever the physical, stochastic, and experimental reasons there are for the variability in CR values, it remains true that under some conditions, plants uptake very small amounts of radionuclides while under other conditions, plants can concentrate radionuclides to a great degree. This generic, albeit simplistic, approach to modeling plant uptake is validated by using distributions of reported CR values that can represent the uncertainty and the variability in the process and measurement of plant uptake for native species.

5.6 Native Versus Agricultural Plant CRs

Concentration ratio values for native plants should be expected to differ from those for agricultural species. The main difference between the two plant types is that native plants tend to have higher CR values than agricultural plants for a given element. As shown by Sheppard and Evenden (1997), even the broadest distributions chosen to describe variability in agricultural plant CR values fail to capture 34 percent of the variability in CR values for native plants; relatively high CR values lie outside the distributions for agricultural species.

The CR values compiled here were compared to CR values compiled for agricultural species (Table 4, Ng et al. 1982, Baes et al. 1984, and Kennedy and Strenge 1994). The average CR values for native plants tend to exceed mean values for agricultural species by one or two orders of magnitude, though native plant CR averages exceed those for non-native species by three to five orders of magnitude in the case of Th. A two order of magnitude difference is well within the range of expected variability about an average CR value, even in studies with the most careful experimental controls (Kinnear et al. 1981). More importantly, for all the elements (except Th for current species), the range of CR values for native plants encompassed ranges reported for agricultural species (Tables 2 and 3). Similarly, the upper and lower quantiles of the lognormal pdfs developed for each element (Tables 2 and 3) encompassed CR ranges reported for agricultural species (except Pb and Th for current species). For all three exceptions, the lower end of the CR values for native plants were equal to or exceeded the upper end of the CR values for agricultural plants, suggesting that CR values (for the three exceptions) are, at the very least, being modeled conservatively for native plants. Again, high CR values for native plants are not necessarily suspect simply because they exceed those for agricultural plants. As explained in the previous section, there are defensible reasons for retaining the Th data, even though some of the Th data are high relative to expected CR values for agricultural species.

In conclusion, this simple comparison suggests that the CR values compiled here for native plant species are not unreasonably high and should be used in NTS PAs in order to prevent an underestimation of the uptake of radionuclides by native plants.

Table 4
Average CR Values for Native and Agricultural Plants

Radionuclide Element	Mean Native Plant CR		Range of Means, Agricultural Plant CR
	current	future	
Am (analogue for Ac)	2.2E-03	1.9E-03	5.9E-5 to 5.8E-4
Cs	5.4E-01	4.8E-01	2.6E-2 to 2.2E-1
Np (analogue for Pa)	1.1E-01	1.1E-01	2.7E-3 to 1.3E-2
Pb	3.2E-01	4.3E-01	3.2E-3 to 9.0E-3
Pu	1.6E-04	1.7E-04	2.6E-5 to 3.9E-4
Ra	1.7E-01	1.3E-01	1.2E-3 to 7.5E-2
Sr	3.3E+01	3.3E+01	1.3E-1 to 1.6E+0
Tc	3.7E+00	1.2E+00	7.3E-1 to 4.4E+1
Th	1.4E+00	6.0E-01	3.4E-5 to 6.6E-3
U	2.9E-01	3.1E-01	1.3E-3 to 1.7E-2

6.0 Biomass Turnover

6.1 Overview

This chapter addresses the parameter selection of the amount of contaminated plant material produced annually (biomass productivity) or released to the environment through the shedding of vegetation (litterfall). This component of the plant uptake model is illustrated in Step Three of Figure 7.

Productivity represents the sum total of a plant's ability to acquire resources of all kinds (e.g., water, light, nutrients) and survive when resources are scarce or unavailable. Productivity is a gross plant- or community-level response to the conditions at a site. It is also a highly variable response that differs from species to species, site to site, season to season, and year to year. The single, largest controlling factor to productivity in southwest deserts is precipitation. Other physiological (ability to tolerate drought or high temperatures, for example) or abiotic (such as climatic or edaphic constraints on growth) factors also operate with precipitation to control productivity. The relative importance of these constraints can vary considerably, both temporally and spatially.

Over the lifetime of an individual plant, biomass not lost over short time scales through such processes as leaf shedding and herbivory is eventually lost upon the plant's death. Biomass gains and losses (which combined are termed "biomass turnover") within plant communities also balance over long time scales as individuals within the community die and are replaced.

Of the abiotic factors affecting productivity at the NTS, some years are favorable for some or all of the lifeforms present, while other years are less favorable for some or all of the lifeforms present. The possibility of a correlation in productivity among the lifeforms exists (with some species responding similarly to environmental cues and others responding quite differently), though the existing data are too limited to defensibly establish these correlations.

6.2 Assumptions and Uncertainties

The major assumption made in compiling and presenting data is that the total amount of biomass produced within a year can serve as an appropriate analogue for the amount of biomass that is shed in a year, or vice versa. This assumption holds true for long-term averages of productivity and litterfall in shrubland and woodland areas of the Great Basin north of the NTS (Passey et al. 1982). Assuming equivalency of productivity and litterfall allows the prediction of biomass turnover when only productivity or litterfall data are available. This assumption also serves to increase the total number of data points usable for predicting biomass turnover when both types of data are available.

Another assumption made is that productivity among the lifeforms is uncorrelated. Ignoring possible correlations would produce the greatest error in simulations where, in reality, two highly productive lifeforms are negatively correlated but the simulations' sampling procedure pulls out high values for each, resulting in simulated doses and fluxes exceeding expected values. Error could also occur in the opposite direction; if two low values are sampled when one should be high, the result would be simulated doses and fluxes that fall below expected values. The correlations could be evaluated probabilistically to determine if resolving the uncertainty would significantly alter the conclusions. If sensitivity analyses show this overestimation causes a false indication of failure to meet the performance objectives, then the benefit of collecting additional data to reduce the uncertainty in the correlations should be further evaluated. However, it is unlikely that there is a cost-effective method for reducing the uncertainty in the correlations, as field studies would require intensive sampling over long observation periods and the data would be of limited value given the uncertainty in future climatic conditions.

6.3 Data Compilation (Current Shrubland)

Estimates of current shrubland productivity and litterfall were compiled from studies at various NTS locations, including areas within both the Mojave and Transitional Deserts (Strojan et al. 1979, Hunter and Medica 1989, and Turner and Randall 1989). The data represent a total of 12 years with both relatively large and small productivity measurements for all the lifeforms. The compilation of data from across the NTS is consistent with an NTS study by Hunter and Medica (1989) which found no significant differences among different basins for the total amount of biomass per hectare; these results indicate that the most important abiotic constraints to site-wide productivity operate at regional scales and produce similar community-level vegetation responses even among seemingly different areas within the NTS boundary. The results are also consistent with the assumption that precipitation (as expressed by effective moisture) is the single most important constraint on plant communities at the NTS. Ultimately, the proposed conceptual model of community changes through time conforms to the results by Hunter and Medica (1989) in assuming changes in both the total and relative percentages of lifeforms are driven by changes in the amount of effective moisture.

The data were treated as follows to compile litterfall and annual net primary productivity (ANP) data:

1. Litterfall was reported for two years in Strojan et al. (1979). The data were given by species, so it was possible to group the data into lifeform categories. There was one category in the report ("others") for which litterfall was estimated, not measured. The average relative

percentages of measured shrub and perennial litterfall were applied to this value to estimate the approximate contribution of each lifeform to the unmeasured portion of litterfall.

2. Turner and Randall (1989) report ANP for shrub and perennial species for six years and productivity of annuals for 11 years. There are three additional years with total productivity of non-annuals, though the data are not given by species; similar to the approach outlined above, the average relative percentages of measured shrub and perennial productivity were applied to these ANP totals to approximate the relative contribution of each lifeform. Turner and Randall (1989) also provide estimates of annual standing crop biomass (ASC) for two years. The average ratio of ANP to ASC was determined for perennial and shrub species. With these ratios, ANP could be estimated when only ASC was given.

3. Standing biomass estimates of shrubs and perennials were given in Hunter and Medica (1989) for 18 plots across the NTS. These ASC values were converted to estimates of ANP with the ratios of ANP/ASC determined from Turner and Randall (1989). Productivity of annuals was reported for seven plots located within five different alluvial basins or valleys at the NTS.

Appendix C includes the data for biomass productivity and litterfall for current shrubland conditions.

6.4 Statistical Analyses and Results (Current Shrubland)

Beta distributions were determined to be the best options for representing the biomass turnover data, because of their flexibility in form and because they can be bound at a maximum value. The criterion that each distribution be bound at a maximum was deemed necessary since the productivity of individuals is limited at some upper value. The observed maximum was set as the upper bound, assuming this value reasonably represents the most growth that will occur for each lifeform under the particular sets of conditions at the analogue sites. Whether lognormal or normal, a distribution that is unimodal can be described with a beta function. Though not presented, histograms for each data set were examined for unimodality and all data sets passed this criterion. The cumulative probability distributions for each data set are shown in Figure 12. The statistical parameters for each data set are given in Table 5.

6.5 Data Compilation (Potential Future Communities)

The data used for estimating productivity and litterfall for future communities came from a single study conducted within Great Basin shrubland and open juniper woodland ecosystems across northern Nevada, central and northern Utah, southern Idaho, and west-central Wyoming

(Passey et al. 1982). The shrubland sites are representative of those currently found in the northern half of the NTS. The juniper woodland sites are within the Great Basin piñon-juniper range (as defined by Miller and Wigand 1994), also encompassing the NTS.

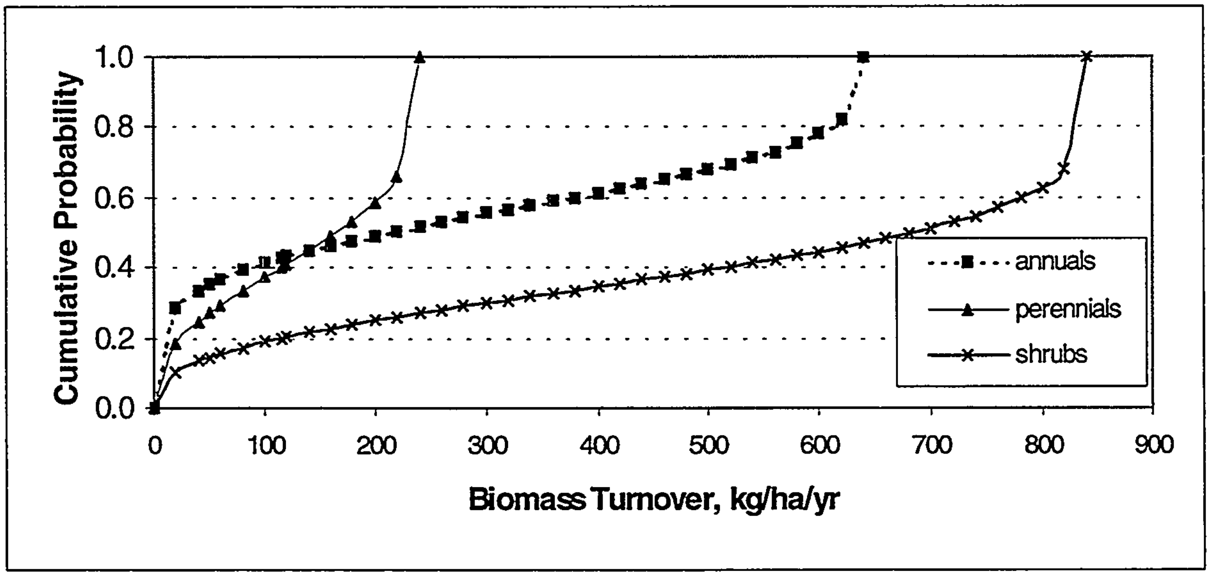

Figure 12

Biomass Turnover Cumulative Probability Distributions for Current Shrubland

Table 5

Statistical Parameters of Biomass Turnover Data for Current Conditions

Parameter, kg/ha/yr	Lifeform			Site-Wide Total
	annual	perennial	shrub	
number of observations	20	29	29	11
mean	140	91	306	485
median	52	80	276	350
minimum	<1	2	120	194
maximum	644	242	842	1,326
standard deviation	180	65	175	337
α^a	0.22	0.38	0.36	na
β^a	0.28	0.27	0.21	na

[a] Scale parameter for beta distribution.

Only sites with woodlands or annual precipitation required for woodland development at the NTS were considered. At relatively cool locations in the northern Great Basin, junipers require approximately 20 cm of annual precipitation. At relatively warm locations in the southern

Mojave Desert, juniper and piñon-juniper woodlands persist in regions that receive 25 to 33 cm of precipitation annually (Brown et al. 1997a). Twelve sites were thus deemed appropriate as analogues for future conditions at the NTS, with average annual precipitation between 20 and 30 cm. Two of the sites support open juniper woodland-shrubland ecosystems, and the remaining ten sites support Great Basin shrub-grass ecosystems. Increased infiltration will produce some variation of these communities.

Pertinent data collected for a ten year period (1960-1969) include: species abundance, yearly productivity by species, and total yearly site litterfall. Not all 12 sites were studied each year, though all have data for 1961 through 1967. Two sites were studied for all ten years and three sites have data spanning eight years. With the data given at the species level it was possible to combine the data into lifeform groups.

Because litterfall was given only as a site total for each year, it was necessary to estimate the litterfall contributed by each lifeform. The amount of litterfall by a lifeform was calculated by multiplying the total litterfall by the relative percent productivity of that lifeform on a per year and per site basis. This assumes that for each unit of productivity, an equally proportionate amount of litterfall is produced. Thus, the distribution of litterfall among the lifeforms was weighted towards those that produce more biomass.

There were a few instances for which the productivity of annuals was reported as zero. While there is some slight chance that absolutely no annuals grew at these sites during these years, it is more likely that sampling techniques failed to detect measurable amounts of annuals. In these cases, the zero was changed to one half of the lowest value recorded for annuals for a given data set, an approach analogous to setting non-detections to one half the detection limit in chemical analyses. This assumes that the reported zero value represents some small, undetected number greater than zero and that the lowest recorded value represents the lowest detection limit for the sampling techniques used.

Appendix C includes the data for biomass productivity and litterfall for potential future conditions.

6.6 Statistical Analyses and Results (Potential Future Communities)

Whether short-term productivity and litterfall data can be used interchangeably was tested using data found in Passey et al. (1982). Specific details of the data screening and compilation are presented in the previous section. In the analysis presented here, total yearly site-wide productivity and litterfall data for 12 sites and from seven to ten years were used, for a total of 93 pairs of data. Because the data are paired by site, a t-test for the differences between population means of dependent variables was performed. Assumptions of the t-test (i.e., normality and equal variances) were investigated prior to performing the t-test and held true for each sample population. The test failed to prove a statistical difference between total site productivity and total site litterfall (see Appendix C for supporting documentation). Thus, the assumption of equivalency of short-term, site-wide productivity and litterfall data is appropriate for the modeling of biomass turnover for potential future communities, and is assumed to hold true for the current community, as well.

Equivalency of productivity and litterfall was also tested with the data for each lifeform, since the uptake model is lifeform-specific. As with the site-wide totals, the assumption of equivalency was determined appropriate for all lifeforms (see Appendix C).

The yearly litterfall data represent the long-term accumulation of dead plant materials in the soil; the data are actually the amount of all litter accumulated at a site up to, and including, that year. Because litterfall was not simply the amount of vegetation shed in a given year, the possibility that litterfall was dependent on previous years' productivity was investigated using a cross-correlation analysis technique (see Appendix D for analysis details).

For all the sites and all the years, the only significant correlation was for productivity and litterfall measured in the same year at one of the shrubland sites (p-value less than $\alpha = 0.05$). The remaining results, though not statistically significant, were used to evaluate possible trends that might lead to different litterfall data transformations. In general, the patterns in productivity were somewhat reflected in the patterns of litterfall. Eight of the 12 sites showed a positive correlation for data measured the same year. Only half of the sites showed litterfall to be positively correlated to the previous year's productivity and slightly more than half of the sites had positive correlations of litterfall to the previous two and three years' productivity. The most consistent trend across sites was the correlation of litterfall with the same year's productivity. Based on these results, the method of calculating litterfall for each lifeform as a function of the productivity of those lifeforms within the same year was deemed acceptable.

The cross-correlation results indicate that on a community level, yearly productivity and long-term litterfall trends can be quite different. A possible explanation is that the abiotic factors controlling productivity, such as precipitation, temperature, and soil nutrient levels, are either not the same factors controlling litterfall or they control leaf shedding to a different degree than they do productivity.

As with biomass turnover for current shrublands, biomass turnover for potential future communities is represented with beta distributions for each lifeform. Statistical parameters used to generate pdfs for each data set (Figures 13 and 14) are included in Tables 6 and 7.

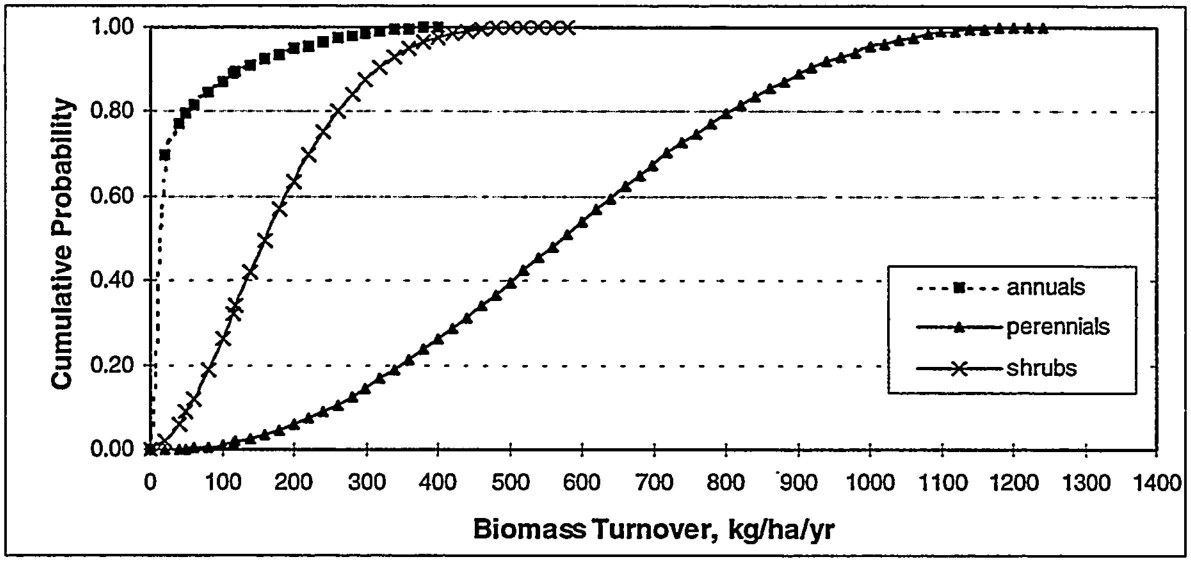

Figure 13

Biomass Turnover Cumulative Probability Distributions for Potential Future Shrublands

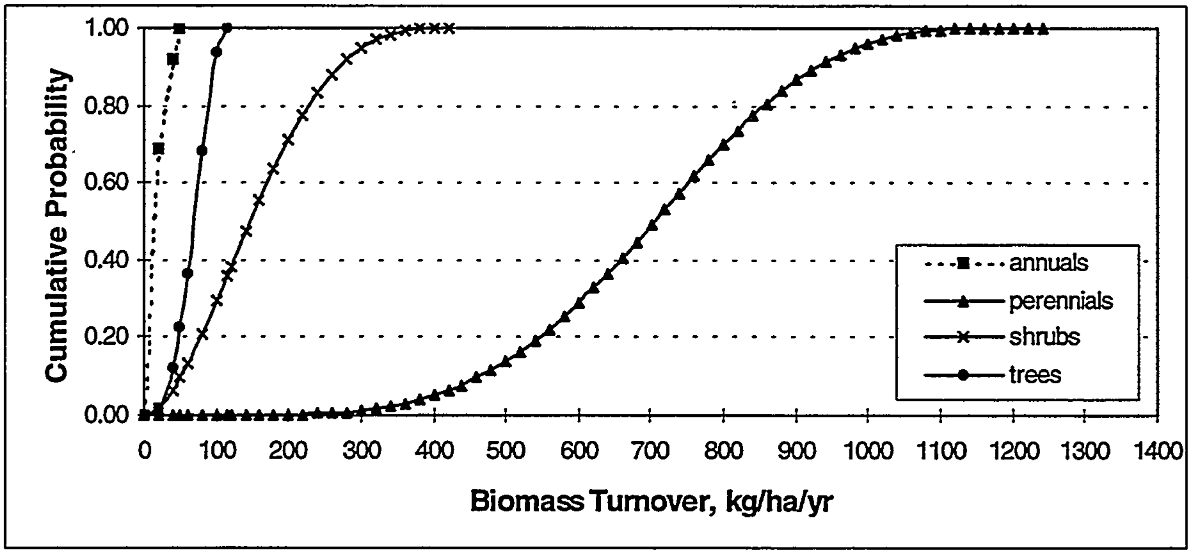

Figure 14

Biomass Turnover Cumulative Probability Distributions for Potential Future Woodlands

Table 6
Statistical Parameters for Biomass Turnover, Potential Future Shrubland

Parameter, kg/ha/yr	Lifeform			Site-Wide Total
	annual	perennial	shrub	
number of observations	158	158	158	158
mean	35	579	175	788
median	9	553	168	780
minimum	1	130	17	271
maximum	399	1253	594	1500
standard deviation	70	246	99	270
α^a	0.15	2.52	1.88	na
β^a	1.51	2.93	4.53	na

[a] Scale parameter for beta distribution.

Table 7
Statistical Parameters for Biomass Turnover, Potential Future Woodland

Parameter, kg/ha/yr	Lifeform				Site-Wide Total
	annual	perennial	shrub	tree	
number of observations	28	28	28	28	28
mean	14	700	155	68	936
median	10	663	134	69	915
minimum	1	437	48	28	666
maximum	47	1244	426	115	1523
standard deviation	14	176	82	22	187
α^a	0.45	6.33	1.89	3.30	na
β^a	1.08	4.92	3.33	2.32	na

[a] Scale parameter for beta distribution.

Average productivity and litterfall were greater in the open woodlands than the shrublands. These differences represent a balance of greater perennial growth and the addition of trees to the community with decreased growth of annuals and shrubs. In both communities, for all the lifeforms, average litterfall was very close to average productivity. This indicates that the litterfall present on a site at any particular time is a good estimator of the long-term average productivity. The converse of this statement is true, as well; average productivity can be used to estimate the long-term biomass turnover in similar communities.

7.0 Conclusions

The proposed plant uptake model for use in PAs for radioactive waste disposal sites at the NTS utilizes multiple soil compartments and plant types. Because regulations governing radioactive waste disposal have protection requirements up to 10,000 years in the future, a conceptual model of potential community changes is also proposed with an estimated post-closure return to current shrubland communities in the near future and, given a shift to conditions of increased effective moisture, a potential future community comprised of more mesic shrubland or woodland species. Over shorter time periods, enhanced infiltration can support ephemeral wetland species that currently occupy sites receiving relatively large amounts of seasonal run-on. Parameter development for each community type is organized by the lifeforms present within current and potential future communities, an ecologically-relevant means of grouping data for individual plant species.

The model is designed to estimate the concentration of radionuclides in plant biomass and the flux of radionuclides past the ground surface. With these, both dose and containment standards for the disposal of radioactive waste can be assessed.

Uncertainty and variability in plant uptake are addressed through the use of pdfs that conform to site-specific data and encompass observed variability in those data along with modeling procedures which address the uncertainty in both the data and model parameters. The relative importance of each model component will be determined upon implementation of the model within a PA analysis. If a PA analysis indicates doses or fluxes may fail to meet the performance objectives, and sensitivity analyses show uncertainty in one or more of the plant parameters to be the cause of this failure, then collecting additional data to reduce the uncertainties in this uptake model should be considered.

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APPENDIX A
ROOT LENGTH DATA AND ANALYSES

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Table A-1
Root Length Data

Item[a]	Species	Length, cm	Root Type[b]	Lifeform[c]	Lifeform Grouping[c]
		Annuals			
72	*Amsinckia rugosa*	120	t	a	a
14	*Amsinckia spectabilis*	13	t	a	a
15	*Astragalus nuttallianus*	13	t	a	a
615	*Avena sativa*	162	t	g	a
56	*Bromus tectorum*	30	t	g	a
77	*Calyptridium umbellatum*	120	t	a	a
21	*Erodium cicutarium*	2	l	a	a
9	*Kallstroemia grandiflora*	22	t	a	a
9	*Kallstroemia grandiflora*	21	l	a	a
26	*Linanthus bigelovii*	10	t	a	a
29	*Mentzelia albicaulis*	11	t	a	a
805	*Mentzelia albicaulis*	12	t	a	a
10	*Pectis prostrata*	13	t	a	a
33	*Phacelia tanacetifolia*	18	t	a	a
33	*Phacelia tanacetifolia*	6	l	a	a
34	*Plantago insularis*	13	t	a	a
35	*Rafinesquia neomexicana*	5	l	a	a
1	*Amaranthus palmeri*	10	t	a	a
1	*Amaranthus palmeri*	25	l	a	a
3	*Aster tanacetifolius*	15	t	a	a
3	*Aster tanacetifolius*	6	l	a	a
73	*Collomia linearis*	120	t	a	a
74	*Gayophytum diffusum*	120	t	a	a
		Perennials			
837	*Ambrosia (Franseria) deltoidea*	38	t	p	p
838	*Ambrosia (Franseria) deltoidea*	18	t	p	p
839	*Ambrosia (Franseria) deltoidea*	180	t	p	p
839	*Ambrosia (Franseria) deltoidea*	140	l	p	p
238	*Ambrosia (Franseria) psilostachya*	183	t	p	p
356	*Anemone zephyra*	15	t	p	p
356	*Anemone zephyra*	18	l	p	p
603	*Aristida purpurea*	122	t	g	p

Refer to footnotes at end of table.

Table A-1 *(Continued)*

Root Length Data

Item[a]	Species	Length, cm	Root Type[b]	Lifeform[c]	Lifeform Grouping[c]
603	*Aristida purpurea*	18	l	g	p
266	*Astragalus arrectus*	183	t	p	p
266	*Astragalus arrectus*	61	l	p	p
409	*Astragalus arrectus*	178	t	p	p
788	*Astragalus cobrensis*	183	t	p	p
	Astragalus goniatus	60	t	p	p
	Astragalus spp.	120	t	p	p
	Ceratoides (Eurotia) lanata	180	t	p	p
381	*Cryptantha flava*	91	t	p	p
619	*Curcurbita foetidissima*	122	t	p	p
373	*Eriogonum alatum*	64	t	p	p
373	*Eriogonum alatum*	81	l	p	p
349	*Eriogonum flavum*	91	t	p	p
64	*Eriogonum heracleoides*	235	t	p	p
803	*Eriogonum spp.*	122	t	p	p
374	*Eriogonum subalpinum*	104	t	p	p
374	*Eriogonum subalpinum*	122	l	p	p
804	*Euphorbia spp.*	6	t	p	p
840	*Krameria canescens*	18	t	p	p
787	*Lepidium montanum*	30	t	p	p
197	*Muhlenbergia montana*	81	t	p	p
197	*Muhlenbergia montana*	17	l	p	p
822	*Muhlenbergia montana*	85	t	p	p
822	*Muhlenbergia montana*	52	l	p	p
827	*Muhlenbergia montana*	104	t	p	p
827	*Muhlenbergia montana*	122	l	p	p
834	*Muhlenbergia montana*	82	t	p	p
834	*Muhlenbergia montana*	40	l	p	p
195	*Muhlenbergia montana*	23	t	p	p
195	*Muhlenbergia torreyi*	127	t	p	p
394	*Oenothera coronopifolia*	152	t	p	p
807	*Oenothera spp.*	137	t	p	p
807	*Oenothera spp.*	137	l	p	p
387	*Oenothera strigosa*	53	t	p	p
387	*Oenothera strigosa*	76	l	p	p
841	*Opuntia arbuscula*	2	t	p	p

Refer to footnotes at end of table.

Table A-1 *(Continued)*
Root Length Data

Item[a]	Species	Length, cm	Root Type[b]	Lifeform[c]	Lifeform Grouping[c]
841	*Opuntia arbuscula*	300	l	p	p
39	*Opuntia engelmanii*	25	t	p	p
40	*Opuntia engelmanii*	15	t	p	p
40	*Opuntia engelmanii*	50	l	p	p
41	*Opuntia leptocaulis*	15	t	p	p
41	*Opuntia leptocaulis*	10	l	p	p
42	*Opuntia leptocaulis*	8	t	p	p
42	*Opuntia leptocaulis*	61	l	p	p
43	*Opuntia versicolor*	30	t	p	p
44	*Opuntia versicolor*	25	t	p	p
786	*Oryzopsis hymenoides*	122	t	g	p
60	*Penstemon glabra*	160	t	p	p
60	*Penstemon glabra*	60	l	p	p
359	*Penstemon glaucus*	36	t	p	p
359	*Penstemon glaucus*	91	l	p	p
388	*Penstemon unilateralis*	53	t	p	p
611	*Psoralea spp.*	213	t	p	p
609	*Psoralea tenuiflora*	274	t	p	p
11	*Solanum elaeagniflolium*	15	t	p	p
395	*Solidago decumbens*	107	t	p	p
	Sphaeralcea coccinea	180	t	p	p
810	*Sphaeralcea spp.*	229	t	p	p
755	*Sporobolus airoides*	457	t	g	p
756	*Sporobolus airoides*	823	t	g	p
736	*Stipa comata*	152	t	g	p
801	*Stipa comata*	168	t	g	p
	Stipa comata	107	t	g	p
	Stipa comata	63	t	g	p
	Stipa comata	99	t	g	p
	Stipa comata	110	t	g	p
	Stipa comata	85	t	g	p
55	*Stipa lettermani*	80	t	g	p
468	*Stipa richardsonii*	183	t	g	p
122	*Stipa spartea*	66	t	g	p
122	*Stipa spartea*	30	l	g	p
	Stipa spartea	80	t	g	p
	Stipa spartea	102	t	g	p

Refer to footnotes at end of table.

Table A-1 *(Continued)*
Root Length Data

Item[a]	Species	Length, cm	Root Type[b]	Lifeform[c]	Lifeform Grouping[c]
	Stipa spartea	68	t	g	p
	Stipa spartea	85	t	g	p
	Stipa spartea	105	t	g	p
	Stipa spartea	60	t	g	p
	Stipa spartea	127	t	g	p
57	*Achillea lanulosa*	14	t	p	p
57	*Achillea lanulosa*	60	l	p	p
390	*Achillea millefolium*	64	t	p	p
391	*Achillea millefolium*	23	t	p	p
460	*Achillea millefolium*	30	t	p	p
472	*Achillea millefolium*	183	t	p	p
51	*Agropyron inerme*	10	t	g	p
262	*Agropyron inerme*	152	t	g	p
261	*Agropyron spicatum*	152	t	g	p
542	*Agropyron spicatum*	183	t	g	p
399	*Allium cernuum*	15	t	p	p
761	*Anemopsis californica*	122	t	p	p
207	*Antennaria parvifolia*	36	t	p	p
207	*Antennaria parvifolia*	13	l	p	p
208	*Antennaria parvifolia*	36	t	p	p
208	*Antennaria parvifolia*	27	l	p	p
209	*Antennaria parvifolia*	48	t	p	p
209	*Antennaria parvifolia*	15	l	p	p
462	*Antennaria spp.*	152	t	p	p
474	*Antennaria spp.*	91	t	p	p
341	*Antennaria umbrinella*	20	t	p	p
367	*Arenaria fendleri*	117	t	p	p
367	*Arenaria fendleri*	61	l	p	p
368	*Arenaria fendleri*	38	t	p	p
403	*Arenaria sajanensis*	76	t	p	p
458	*Arnica cordifolia*	61	t	p	p
369	*Arnica cordifolia*	142	t	p	p
204	*Artemesia frigida*	94	t	p	p
204	*Artemesia frigida*	16	l	p	p
205	*Artemesia frigida*	97	t	p	p
205	*Artemesia frigida*	22	l	p	p

Refer to footnotes at end of table.

Table A-1 *(Continued)*
Root Length Data

Item[a]	Species	Length, cm	Root Type[b]	Lifeform[c]	Lifeform Grouping[c]
206	*Artemesia frigida*	97	t	p	p
206	*Artemesia frigida*	22	l	p	p
384	*Artemesia frigida*	46	t	p	p
384	*Artemesia frigida*	91	l	p	p
385	*Artemesia frigida*	183	t	p	p
392	*Aster commutatus*	36	t	p	p
66	*Balsamorhiza sagittata*	270	t	p	p
267	*Balsamorhiza sagittata*	274	t	p	p
267	*Balsamorhiza sagittata*	91	l	p	p
107	*Bouteloua gracilis*	45	t	g	p
201	*Bouteloua gracilis*	102	t	g	p
201	*Bouteloua gracilis*	24	l	g	p
202	*Bouteloua gracilis*	109	t	g	p
202	*Bouteloua gracilis*	19	l	g	p
203	*Bouteloua gracilis*	84	t	g	p
203	*Bouteloua gracilis*	18	l	g	p
602	*Bouteloua gracilis*	98	t	g	p
861	*Bouteloua gracilis*	122	t	g	p
861	*Bouteloua gracilis*	46	l	g	p
400	*Calochortus gunnisoni*	13	t	p	p
456	*Carex geyeri*	122	t	se	p
469	*Carex geyeri*	183	t	se	p
52	*Carex geyeri*	160	t	se	p
346	*Castilleja brachyantha*	30	t	p	p
386	*Castilleja linariaefolia*	25	t	p	p
386	*Castilleja linariaefolia*	61	l	p	p
68	*Clematis hirsutissima*	140	t	p	p
753	*Distichlis spicata*	234	t	se	p
851	*Elymus canadensis*	266	t	g	p
752	*Elymus condensatus*	366	t	g	p
370	*Epilobium angustifolium*	107	t	p	p
371	*Epilobium angustifolium*	122	t	p	p
461	*Galium boreale*	152	t	p	p
471	*Galium boreale*	183	t	p	p
270	*Haplopappus racemosus*	335	t	p	p
270	*Haplopappus racemosus*	61	l	p	p

Refer to footnotes at end of table.

Table A-1 *(Continued)*
Root Length Data

Item[a]	Species	Length, cm	Root Type[b]	Lifeform[c]	Lifeform Grouping[c]
350	*Heuchera bracteata*	41	t	p	p
271	*Heuchera glabella*	183	t	p	p
271	*Heuchera glabella*	30	l	p	p
789	*Hymenoxys acaulis*	24	t	p	p
123	*Koeleria cristata*	71	t	g	p
315	*Lithospermum caroliniense*	213	t	p	p
67	*Lithospermum ruderale*	300	t	p	p
272	*Lithospermum ruderale*	183	t	p	p
272	*Lithospermum ruderale*	70	l	p	p
273	*Lupinus leucophyllus*	168	t	p	p
273	*Lupinus leucophyllus*	91	l	p	p
408	*Lupinus leucophyllus*	168	t	p	p
274	*Lupinus obtusilobis*	335	t	p	p
274	*Lupinus obtusilobis*	122	l	p	p
407	*Lupinus obtusilobis*	335	t	p	p
65	*Lupinus spp.*	240	t	p	p
612	*Lygodesmia juncea*	213	t	p	p
345	*Phacelia sericia*	23	t	p	p
382	*Phacelia splendens*	122	t	p	p
347	*Phlox caespitosa*	23	t	p	p
347	*Phlox caespitosa*	81	l	p	p
62	*Phlox longifolia*	75	t	p	p
54	*Poa secunda*	35	t	g	p
260	*Poa secunda*	61	t	g	p
406	*Potentilla diversifolia*	61	t	p	p
63	*Potentilla gracilis*	75	t	p	p
275	*Potentilla gracilis*	229	t	p	p
275	*Potentilla gracilis*	30	l	p	p
383	*Potentilla gracilis*	107	t	p	p
809	*Senecio spp.*	91	t	p	p
351	*Senecio taraxaciodes*	30	t	p	p
348	*Silene acaulis*	15	t	p	p
76	*Silene spp.*	120	t	p	p
340	*Stellaria crassifolia*	15	t	p	p
760	*Suaeda spp.*	213	t	p	p
344	*Trifolium dasyphyllum*	30	t	p	p

Refer to footnotes at end of table.

Table A-1 *(Continued)*

Root Length Data

Item[a]	Species	Length, cm	Root Type[b]	Lifeform[c]	Lifeform Grouping[c]
597	*Trifolium hybridum*	61	t	p	p
595	*Trifolium pratense*	173	t	p	p
596	*Trifolium pratense*	145	t	p	p
401	*Zygadenus elegans*	13	t	p	p
		SHRUBS			
	Artemesia cana	240	t	s	s
790	*Artemesia spinescens*	152	t	s	s
179	*Artemesia tridentata*	152	t	s	s
179	*Artemesia tridentata*	722	l	s	s
180	*Artemesia tridentata*	213	t	s	s
181	*Artemesia tridentata*	160	t	s	s
181	*Artemesia tridentata*	152	l	s	s
182	*Artemesia tridentata*	183	t	s	s
182	*Artemesia tridentata*	152	l	s	s
183	*Artemesia tridentata*	183	t	s	s
183	*Artemesia tridentata*	122	l	s	s
184	*Artemesia tridentata*	168	t	s	s
184	*Artemesia tridentata*	122	l	s	s
818	*Artemesia tridentata*	914	t	s	s
	Artemesia tridentata	150	t	s	s
	Artemesia tridentata	110	t	s	s
765	*Atriplex canescens*	305	t	s	s
766	*Atriplex canescens*	762	t	s	s
	Atriplex canescens	80	t	s	s
	Atriplex canescens	110	t	s	s
794	*Atriplex confertifolia*	152	t	s	s
	Atriplex nuttallii	180	t	s	s
767	*Atriplex torreyi*	274	t	s	s
819	*Chrysothamnus nauseosus*	457	t	s	s
	Chrysothamnus nauseosus	180	t	s	s
	Chrysothamnus nauseosus	100	t	s	s
	Chrysothamnus nauseosus	300	t	s	s
38	*Encelia farinosa*	55	t	s	s
38	*Encelia farinosa*	60	l	s	s
792	*Ephedra viridis*	549	t	s	s
78	*Haplopappus lanuginosus*	200	t	s	s

Refer to footnotes at end of table.

Table A-1 *(Continued)*
Root Length Data

Item[a]	Species	Length, cm	Root Type[b]	Lifeform[c]	Lifeform Grouping[c]
328	*Haplopappus tenuisectus*	549	t	s	s
328	*Haplopappus tenuisectus*	122	l	s	s
764	*Hymenoclea monogyra*	305	t	s	s
47	*Larrea tridentata*	35	t	s	s
47	*Larrea tridentata*	300	l	s	s
48	*Larrea tridentata*	107	t	s	s
48	*Larrea tridentata*	210	l	s	s
763	*Pluchea sericea*	762	t	s	s
424	*Salvia apiana*	152	t	s	s
769	*Sarcobatus vermiculatus*	1737	t	s	s
795	*Sarcobatus vermiculatus*	579	t	s	s
426	*Yucca whiplei*	76	t	s	s
412	*Arctostaphylos*	274	t	s	s
412	*Arctostaphylos*	76	l	s	s
854	*Arctostaphylos glandulosa*	518	t	s	s
816	*Arctostaphylos glauca*	259	t	s	s
833	*Arctostaphylos uva-ursi*	61	t	s	s
465	*Arctostaphylos uva-ursi*	91	t	s	s
477	*Arctostaphylos uva-ursi*	183	t	s	s
464	*Berberis repens*	183	t	s	s
476	*Berberis repens*	183	t	s	s
459	*Ceanothus crassifolius*	137	t	s	s
413	*Ceanothus leucodermis*	366	t	s	s
855	*Ceanothus leucodermis*	366	t	s	s
419	*Ceanothus oliganthus*	183	t	s	s
814	*Ceanothus spp.*	366	t	s	s
856	*Eriodictyon spp.*	137	t	s	s
856	*Eriodictyon spp.*	91	l	s	s
422	*Eriogonum fasciculatum*	122	t	s	s
799	*Gutierrezia divaricata*	244	t	s	s
176	*Gutierrezia sarothrae*	213	t	s	s
176	*Gutierrezia sarothrae*	61	l	s	s
605	*Gutierrezia sarothrae*	198	t	s	s
279	*Rosa sufflata*	640	t	s	s
467	*Rosa woodsii*	91	t	s	s
479	*Rosa woodsii*	183	t	s	s

Refer to footnotes at end of table.

Table A-1 *(Continued)*
Root Length Data

Item[a]	Species	Length, cm	Root Type[b]	Lifeform[c]	Lifeform Grouping[c]
475	*Symphoricarpos albus*	183	t	s	s
463	*Symphoricarpos albus*	152	t	s	s
817	*Symphoricarpos spp.*	183	t	s	s
TREES					
696	*Acer rubrum*	2500	t	t	t
784	*Acer saccharinum*	91	t	t	t
784	*Acer saccharinum*	91	l	t	t
223	*Acer sp.*	2438	l	t	t
796	*Amelanchier utahensis*	640	t	t	t
420	*Cercocarpus betuloides*	152	t	t	t
	Cercocarpus montanus	50	t	t	t
	Cercocarpus montanus	40	t	t	t
823	*Cercocarpus montanus*	152	t	t	t
823	*Cercocarpus montanus*	244	l	t	t
828	*Cercocarpus montanus*	152	t	t	t
828	*Cercocarpus montanus*	305	l	t	t
835	*Cercocarpus montanus*	107	t	t	t
835	*Cercocarpus montanus*	152	l	t	t
797	*Cowania stansburiana*	152	t	t	t
798	*Fraxinus anomala*	305	t	t	t
791	*Juniperus monosperma*	579	t	t	t
	Juniperus monosperma	170	t	t	t
	Juniperus monosperma	600	t	t	t
428	*Pinus banksiana*	168	t	t	t
428	*Pinus banksiana*	853	l	t	t
820	*Pinus contorta*	122	t	t	t
820	*Pinus contorta*	488	l	t	t
	Pinus edulis	110	t	t	t
	Pinus edulis	130	t	t	t
	Pinus edulis	600	t	t	t
	Pinus edulis	300	t	t	t
	Pinus edulis	640	t	t	t
811	*Pinus ponderosa*	2438	t	t	t
826	*Pinus ponderosa*	171	t	t	t
826	*Pinus ponderosa*	610	l	t	t
832	*Pinus ponderosa*	85	t	t	t

Refer to footnotes at end of table.

Table A-1 *(Concluded)*

Root Length Data

Item[a]	Species	Length, cm	Root Type[b]	Lifeform[c]	Lifeform Grouping[c]
832	*Pinus ponderosa*	579	l	t	t
	Pinus ponderosa	160	t	t	t
	Pinus ponderosa	150	t	t	t
	Pinus ponderosa	200	t	t	t
698	*Populus euramericana*	1400	t	t	t
776	*Populus fremontii*	610	t	t	t
831	*Populus tremuloides*	73	t	t	t
831	*Populus tremuloides*	610	l	t	t
770	*Prosopis spp.*	1828	t	t	t
771	*Prosopis spp.*	792	t	t	t
687	*Prunus persica*	272	t	t	t
687	*Prunus persica*	305	l	t	t
688	*Prunus persica*	152	t	t	t
688	*Prunus persica*	457	l	t	t
778	*Quercus agrifolia*	1067	t	t	t
415	*Quercus chrysolepis*	732	t	t	t
416	*Quercus dumosa*	244	t	t	t
417	*Quercus dumosa*	853	t	t	t
793	*Quercus gambelii*	396	t	t	t
	Quercus gambelii	200	l	t	t
779	*Quercus lobata*	610	t	t	t
427	*Quercus macrocarpa*	335	t	t	t
785	*Quercus macrocarpa*	457	t	t	t
782	*Quercus maxima*	152	t	t	t
782	*Quercus maxima*	274	l	t	t
813	*Quercus spp.*	853	t	t	t
	Quercus spp.	320	t	t	t
	Quercus spp.	150	t	t	t
	Quercus spp.	175	t	t	t
	Quercus spp.	80	t	t	t
335	*Salix nivalis*	20	t	t	t
812	*Salix spp.*	366	t	t	t
694	*Tamarix spp.*	3000	t	t	t

[a] item number from original database, if available.

[b] l = lateral root; t = vertical root.

[c] a = annual; g = grass; p = perennial; s = shrub; se = sedge; t = tree.

A.1 Exponential Distribution

The assumption of an exponential distribution appears appropriate for the maximum root length statistics provided in Table 1 in Chapter 4.0. The mean of an exponential distribution is equal to its standard deviation, and the median value is less than the mean by a factor of ln(2) (=0.693). The statistics in Table 1 exhibit these properties with the exception of the median/mean ratio for annual plants. This lifeform has the fewest number of observations, however, and the distribution mean is correspondingly uncertain. Figure A-1 shows the likelihood distributions for the mean maximum root length L_j based on the data in Table 1. The likelihood distribution for the mean maximum root length L_j is derived assuming an exponential distribution for individual measurements of maximum root length. The probability density for an observed maximum root length of x is then

$$f(x) = \frac{1}{L_j} e^{-x/L_j} \qquad \text{(Eq. A-1)}$$

Given a set of n independent observations of maximum root length, the likelihood function is given by:

$$L(L_j; x_1, x_2, \dots x_n) = f(x_1)\, f(x_2) \dots f(x_n) = \left(\frac{1}{L_j}\right)^n \exp\left[-\frac{\sum_{i=1}^{n} x_1}{L_j}\right] \qquad \text{(Eq. A-2)}$$

The conditional distribution for the average maximum root length, given the n observations, is then:

$$f(L_j) = \frac{L(L_j; x_1, x_2, \dots x_n)}{\int_{l=0}^{\infty} L(l; x_1, x_2, \dots x_n)} \qquad \text{(Eq. A-3)}$$

The 90 percent confidence interval for L_j for annuals is fairly broad as noted above, ranging from approximately 30 cm to 60 cm. In contrast, perennial plants have a much larger number of observations (196)—enough to establish the mean value for this lifeform with very little uncertainty.

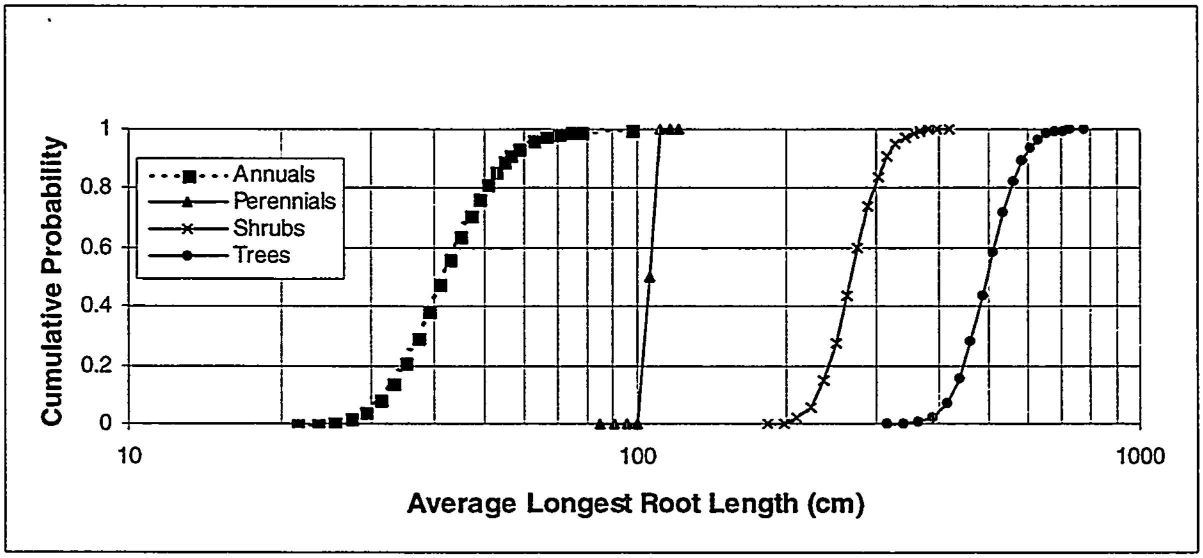

Figure A-1
Likelihood Distributions for L_j

A.2 Species Variability in Maximum Root Length

The plant root length data in Table A-1 have been grouped by lifeform for the purpose of modeling the current and future plant communities, and for analyzing the root length data. The data analysis is based on the assumption that the set of measurements within each lifeform are representative of the measurements that would be made of plants in that lifeform at an RWMS. The measurements may be representative in at least two ways. First, they may approximate a random sample of plants at the site and, therefore, include the same plant species in the same proportions as would occur at the site. Second, the measurements for any particular species in a lifeform may have the same distribution as the measurements for any other species in the same lifeform. In this case, the particular species that are measured to characterize the lifeform need not represent the species that would occur at the site because variations among species are practically irrelevant.

For the data in Table A-1, the particular species and the proportions of individual species may not represent the community that would occur at an RWMS. Data for individual species can be compared against the fitted distribution for the lifeform as a whole, in order to assess the assumption that each species can be described by a common lifeform distribution. A speciesbased analysis tests whether variations among species in the same lifeform are consistent with the assumption that the measurements for all species come from a common lifeform distribution. This consistency test examines the confidence limits for the average root length for individual species, assuming that each species is characterized by an exponential distribution.

The confidence intervals are seen to overlap, and to include the overall average for the lifeform, even in cases where all measurements for the species are above or below the lifeform average. This observation supports the assumption that a common distribution is appropriate for describing the lifeform as a whole.

Data for species with three or more observations of maximum root length were selected from the root length database. Separate plots were generated for each lifeform which include the individual observations of root length for each species (Figures A-2, A-3, and A-4). The best estimate of the population mean, which is the average of all the data points for a lifeform, is also shown on each figure. Only perennials, shrubs, and trees were plotted, as insufficient data were available for annuals. While the variability across species is often quite large, there is considerable overlap of maximum root length data for the species in each lifeform.

Comparing ranges across species (Figures A-2, A-3, and A-4) can be misleading in that the number of observations differ among species. A plot of the upper and lower limits of the 90 percent confidence interval for the average root length as a function of the number of observations (from Equation A-3) can serve as a separate check on whether the data for different species within a lifeform belong to different distributions, given differences in sample sizes for each species (Figure A-5). Take, for example, the non-overlap of perennial species 10 and 15, as plotted in Figure A-1. The average root length for species 10 is 29 cm, based on six observations; thus, the 90 percent confidence interval for the distribution as plotted in Figure A-5, ranges from approximately 17 cm (0.6 * 29 cm) to 116 cm (4.0 * 29 cm). The average value for species 15 is 155 cm, based on three observations; thus, the 90 percent confidence interval for this species ranges from approximately 100 cm (0.65 * 155 cm) to 12,400 cm (80 * 155 cm), indicating that this set of observations, as well as that for species 10, is consistent with a lifeform average of 106 cm.

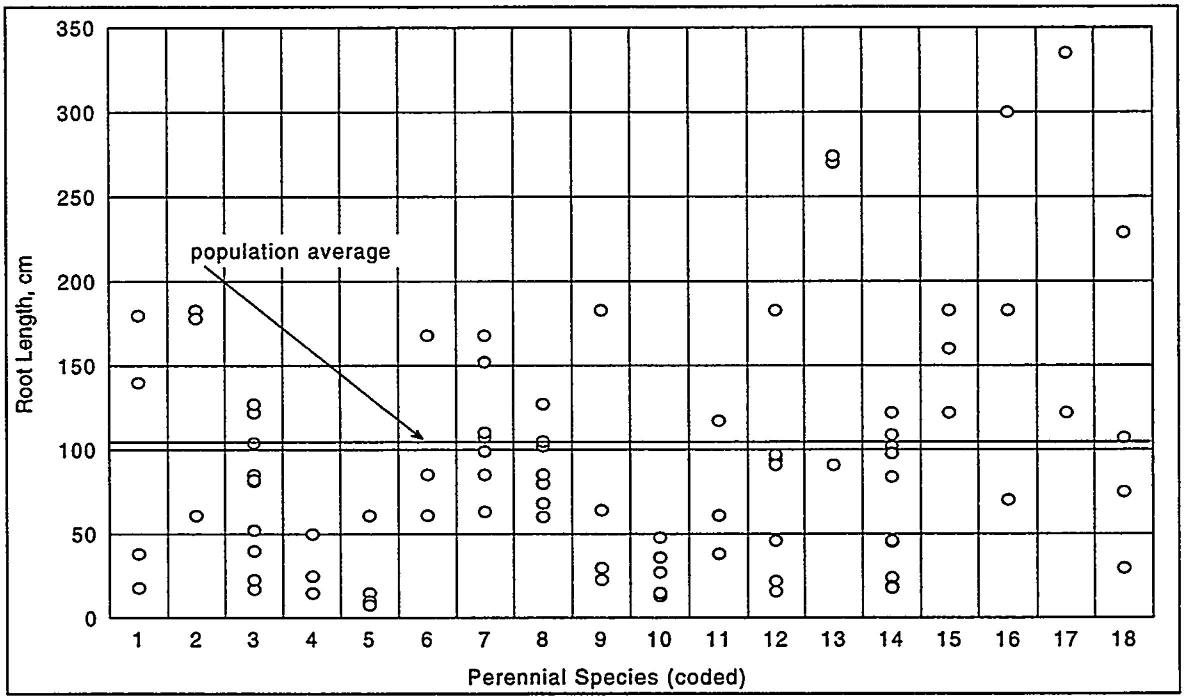

Figure A-2
Select Perennial Species Root Lengths (n≥3)

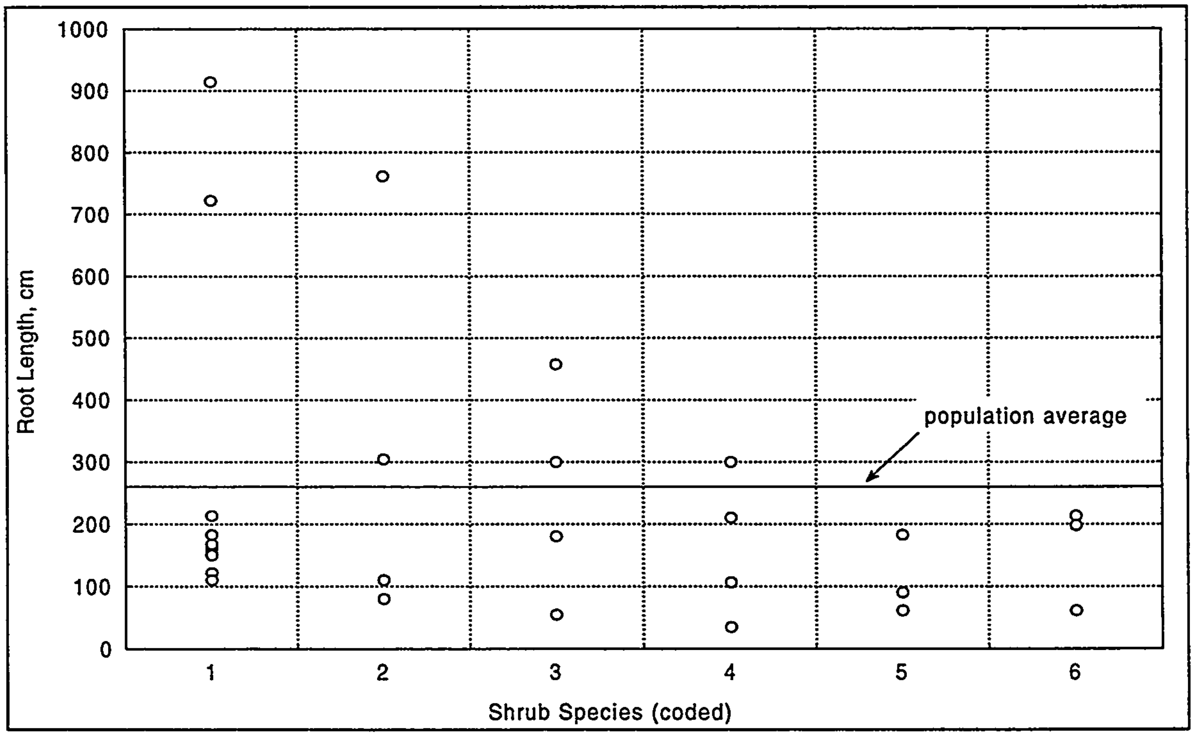

Figure A-3
Select Shrub Species Root Lengths (n≥3)

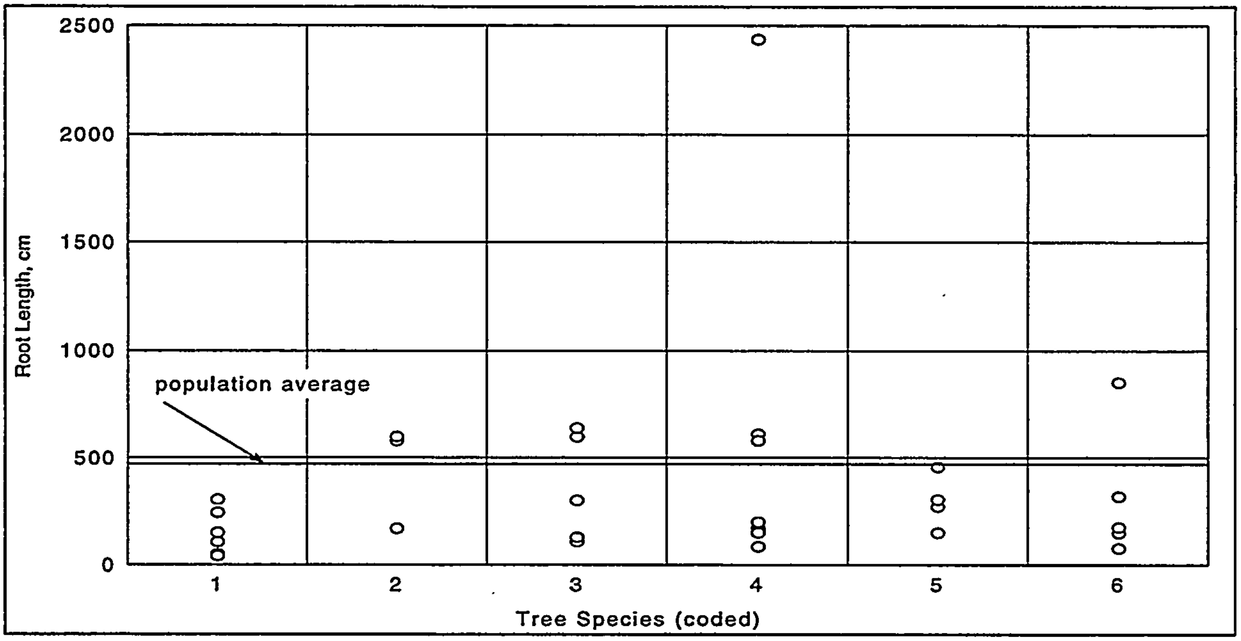

Figure A-4
Select Tree Species Root Lengths (n≥3)

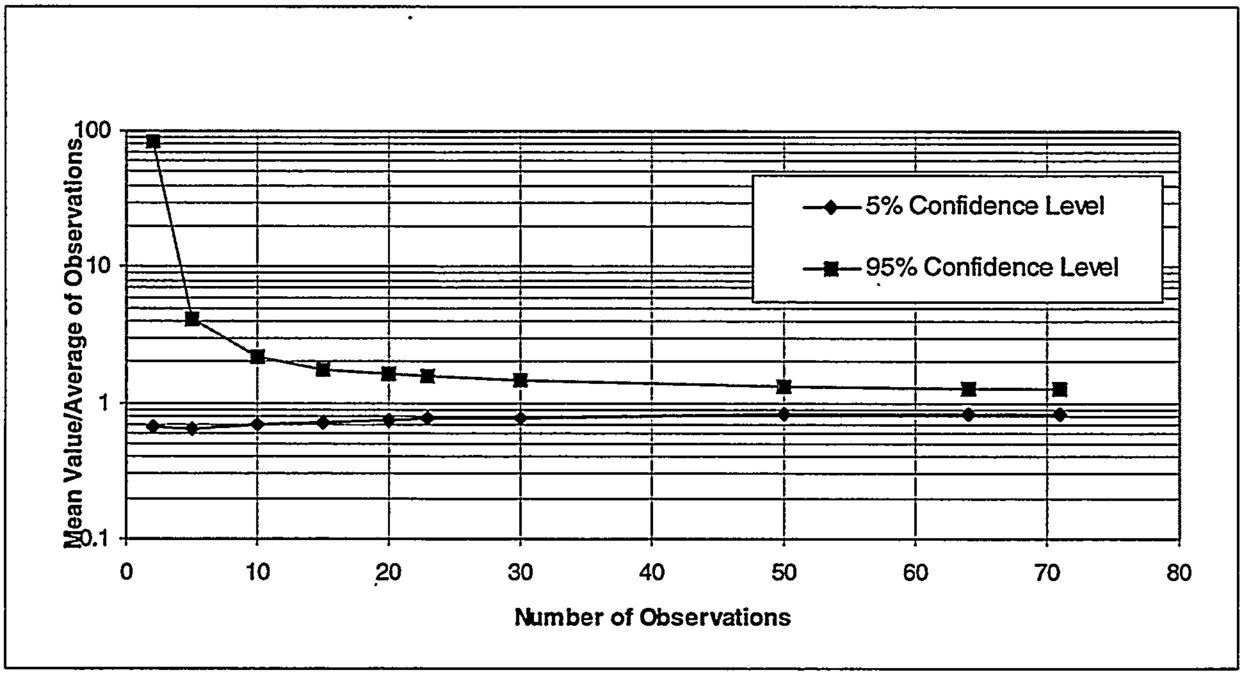

Figure A-5
90% Confidence Interval for Mean Root Length as a Function of Sample Size

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APPENDIX B

CONCENTRATION RATIO DATA AND ANALYSES

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Table B-1
Concentration Ratio Data

Radionuclide	CR	Time[a]	Citation[b]
am	6.00E-05	c	1
am	8.00E-05	c	1
am	1.00E-04	c	1
am	2.30E-04	c	1
am	6.00E-04	c	1
am	6.00E-04	c	1
am	1.40E-03	c	1
am	1.40E-03	c	1
am	1.50E-03	c	1
am	1.50E-03	c	1
am	2.10E-03	c	1
am	1.70E-02	c	1
cs	5.36E-02	c	2
pa	7.00E-03	c	1
pa	1.10E-02	c	1
pa	1.20E-02	c	1
pa	1.30E-02	c	1
pa	1.30E-02	c	1
pa	1.50E-02	c	1
pa	1.10E-01	c	1
pa	1.12E-01	c	1
pa	2.30E-01	c	1
pa	2.40E-01	c	1
pa	2.80E-01	c	1
pa	2.80E-01	c	1
pb	1.42E-03	c	3
pb	5.67E-03	c	3
pb	8.00E-03	c	4
pb	9.20E-03	c	3
pb	9.93E-03	c	3
pb	1.00E-02	c	5
pb	2.20E-02	c	5
pb	1.10E-01	c	4
pb	1.12E-01	c	3
pb	1.20E-01	c	4
pb	1.30E-01	c	4
pb	1.42E-01	c	3
pb	2.90E-01	c	4
pb	5.00E-01	c	4
pb	6.30E-01	c	4

Refer to footnotes at end of table.

Table B-1 *(Continued)*
Concentration Ratio Data

Radionuclide	CR	Time[a]	Citation[b]
pb	6.60E-01	c	4
pb	8.79E-01	c	3
pb	8.80E-01	c	4
pb	9.50E-01	c	4
pb	9.90E-01	c	4
pu	1.40E-05	c	1
pu	1.70E-05	c	1
pu	1.70E-05	c	1
pu	4.30E-05	c	1
pu	4.60E-05	c	1
pu	4.60E-05	c	1
pu	4.80E-05	c	1
pu	5.10E-05	c	1
pu	5.30E-05	c	1
pu	2.54E-04	c	1
pu	2.73E-04	c	1
pu	3.10E-04	c	1
pu	8.60E-04	c	2
ra	4.73E-03	c	3
ra	1.53E-02	c	3
ra	1.96E-02	c	3
ra	2.52E-02	c	6
ra	3.40E-02	c	5
ra	3.74E-02	c	6
ra	4.08E-02	c	3
ra	4.09E-02	c	6
ra	4.10E-02	c	5
ra	4.89E-02	c	3
ra	4.90E-02	c	5
ra	5.61E-02	c	6
ra	7.83E-02	c	3
ra	1.03E-01	c	6
ra	1.25E-01	c	6
ra	1.29E-01	c	6
ra	1.36E-01	c	6
ra	1.40E-01	c	6
ra	1.58E-01	c	6
ra	2.08E-01	c	6
ra	2.19E-01	c	6
ra	2.19E-01	c	6

Refer to footnotes at end of table.

Table B-1 *(Continued)*
Concentration Ratio Data

Radionuclide	CR	Time[a]	Citation[b]
ra	2.70E-01	c	6
ra	2.85E-01	c	6
ra	3.10E-01	c	6
ra	3.38E-01	c	6
ra	3.90E-01	c	6
ra	4.50E-01	c	5
ra	4.80E-01	c	6
ra	7.40E-01	c	5
sr	4.18E+00	c	7
sr	6.16E+01	c	7
th	1.23E-02	c	8
th	2.00E-02	c	9
th	2.66E-02	c	8
th	3.57E-02	c	8
th	4.32E-02	c	8
th	5.37E-02	c	8
th	6.15E-02	c	8
th	6.60E-02	c	8
th	8.00E-02	c	9
th	1.72E-01	c	8
th	1.78E-01	c	8
th	1.94E-01	c	8
th	2.25E-01	c	8
th	3.26E-01	c	8
th	3.30E-01	c	9
th	3.80E-01	c	8
th	4.10E-01	c	9
th	4.60E-01	c	9
th	6.94E-01	c	8
th	1.89E+00	c	8
th	1.90E+00	c	9
th	2.88E+00	c	8
th	1.10E+01	c	9
th	1.10E+01	c	9
u	4.27E-03	c	2
u	5.28E-03	c	3
u	7.95E-03	c	3
u	8.52E-03	c	3
u	9.66E-03	c	3
u	9.66E-03	c	3

Refer to footnotes at end of table.

Table B-1 *(Continued)*
Concentration Ratio Data

Radionuclide	CR	Time[a]	Citation[b]
u	1.70E-02	c	3
u	3.94E-02	c	8
u	4.80E-02	c	8
u	6.00E-02	c	9
u	7.00E-02	c	9
u	7.44E-02	c	8
u	8.80E-02	c	8
u	2.30E-01	c	8
u	2.50E-01	c	7
u	2.70E-01	c	9
u	2.84E-01	c	7
u	2.90E-01	c	9
u	3.19E-01	c	8
u	3.30E-01	c	9
u	3.90E-01	c	9
u	8.09E-01	c	8
u	1.50E+00	c	9
u	1.90E+00	c	9
am	5.00E-05	f	10
am	4.80E-04	f	10
cs	1.20E-02	f	11
cs	1.31E-01	f	11
cs	2.83E-01	f	11
cs	2.95E-01	f	11
cs	3.59E-01	f	11
cs	4.00E-01	f	11
cs	4.34E-01	f	11
cs	4.41E-01	f	11
cs	6.56E-01	f	11
cs	7.62E-01	f	11
cs	1.07E+00	f	11
cs	1.29E+00	f	11
pb	1.64E-01	f	12
pb	2.51E-01	f	12
pb	2.84E-01	f	12
pb	3.66E-01	f	12
pb	5.46E-01	f	12
pb	3.04E+00	f	13
pu	8.00E-06	f	10
pu	5.20E-04	f	10

Refer to footnotes at end of table.

Table B-1 *(Continued)*
Concentration Ratio Data

Radionuclide	CR	Time[a]	Citation[b]
ra	2.20E-03	f	14
ra	2.40E-03	f	12
ra	2.42E-03	f	14
ra	4.40E-03	f	14
ra	4.73E-03	f	14
ra	4.73E-03	f	14
ra	4.76E-03	f	14
ra	5.70E-03	f	12
ra	1.58E-02	f	12
ra	1.82E-02	f	12
ra	4.88E-02	f	12
th	3.15E-05	f	14
th	7.26E-05	f	14
th	7.55E-05	f	14
th	9.13E-05	f	14
th	1.84E-04	f	14
th	5.40E-04	f	14
th	8.15E-04	f	14
th	1.10E-03	f	14
th	2.76E-03	f	14
th	8.00E-03	f	14
th	1.70E-02	f	14
th	2.13E-02	f	14
th	2.79E-02	f	14
th	3.79E-02	f	14
th	4.08E-02	f	14
th	4.74E-02	f	14
th	6.43E-02	f	14
th	8.01E-02	f	14
th	8.97E-02	f	14
th	1.19E-01	f	14
th	1.19E-01	f	14
th	1.37E-01	f	14
th	1.54E-01	f	15
th	2.24E-01	f	15
th	2.37E-01	f	14
th	2.70E-01	f	14
th	2.88E-01	f	14
th	3.54E-01	f	15
th	3.90E-01	f	14

Refer to footnotes at end of table.

Table B-1 *(Continued)*
Concentration Ratio Data

Radionuclide	CR	Time[a]	Citation[b]
th	4.69E-01	f	14
th	5.38E-01	f	14
th	6.99E-01	f	14
th	1.06E+00	f	14
th	2.37E+00	f	14
u	7.00E-04	f	10
u	1.25E-03	f	10
u	1.70E-03	f	12
u	2.20E-03	f	12
u	2.30E-03	f	12
u	3.20E-03	f	12
u	7.69E-03	f	14
u	1.06E-02	f	10
u	1.31E-02	f	10
u	1.67E-02	f	14
u	2.21E-02	f	14
u	2.26E-02	f	14
u	2.50E-02	f	14
u	2.60E-02	f	16
u	2.61E-02	f	14
u	2.85E-02	f	14
u	3.00E-02	f	17
u	3.00E-02	f	17
u	4.53E-02	f	12
u	4.62E-02	f	14
u	7.50E-02	f	16
u	1.00E-01	f	14
u	1.38E-01	f	14
u	1.52E-01	f	15
u	3.60E-01	f	15
u	5.12E-01	f	16
u	5.63E-01	f	13
u	7.32E-01	f	16
u	8.05E-01	f	16
u	1.17E+00	f	16
u	2.10E+00	f	15
u	3.48E+00	f	16

Refer to footnotes at end of table.

Table B-1 *(Concluded)*
Concentration Ratio Data

[a] c = current; f = future.

[b] Citations:

1 = Price (1972 and 1973)
2 = Wenzel et al. (1987)
3 = Dreesen and Marple (1979)
4 = Ibrahim and Whicker (1987)
5 = Simon and Fraley (1986)
6 = Ibrahim and Whicker (1988b)
7 = Fresquez et al. (1995)
8 = Ibrahim and Whicker (1988a)
9 = Ibrahim et al. (1982)
10 = Garten (1980)
11 = Livens et al. (1991)
12 = Mahon and Mathewes (1983)
13 = Dunn (1981)
14 = Titaeva et al. (1979)
15 = Sheppard and Thibault (1981)
16 = Walker (1978)
17 = Sheppard and Sheppard (1985)

Table B-2

Results of Normality Tests on Log-Transformed Concentration Ratio Data for Current Shrubland Species

Radionuclide Element	Shapiro-Wilk Test	Lilliefors Test
Am (analogue for Ac)	p<0.35	p>0.20
Cs[a]	-----	-----
Np (analogue for Pa)	p<0.01	p<0.01
Pb	p<0.03	p<0.10
Pu	p<0.10	p<0.01
Ra	p<0.49	p>0.20
Sr[1]	-----	-----
Tc[1]	-----	-----
Th	p<0.36	p>0.20
U	p<0.17	p<0.10
all data (generic)	p<0.00	p<0.01

[a] There are insufficient data to run the normality tests.

Table B-3

Results of Normality Tests on Log-Transformed Concentration Ratio Data for Potential Future Species

Radionuclide Element	Shapiro-Wilk Test	Lilliefors Test
Am (analogue for Ac)	p<0.35	p>0.20
Cs	p<0.04	p<0.05
Np (analogue for Pa)	p<0.01	p<0.01
Pb	p<0.04	p<0.01
Pu	p<0.22	p<0.05
Ra	p<0.03	p<0.20
Sr[a]	-----	-----
Tc	p<0.39	p>0.15
Th	p<0.00	p<0.01
U	p<0.43	p>0.20
all data (generic)	p<0.00	p<0.01

[a] There are insufficient data to run the normality tests.

Table B-4

Geometric Standard Deviations of Concentration Ratio Distributions

Radionuclide Element	Current Shrubland Species[a]	Potential Future Species
Am (for Ac)	0.71	0.72
Cs	--	0.56
Np (for Pa)	0.66	0.66
Pb	0.90	0.86
Pu	0.55	0.62
Ra	0.52	0.73
Sr	--	--
Tc	--	0.66
Th	0.81	1.26
U	0.79	0.91
all data (generic)	1.34	1.29

[a] Dashed lines indicate insufficient data to perform analysis.

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APPENDIX C

BIOMASS TURNOVER DATA AND ANALYSES

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Table C-1
Productivity and Litterfall Data for Current Shrubland Community

Location	Year	Lifeform			Data Type[a]	Citation[b]
		shrub	perennial	annual		
Frenchman Flat	1987	217	49	--	anp	1
Frenchman Flat	1987	174	37	--	anp	1
Frenchman Flat	1987	357	20	--	anp	1
Frenchman Flat	1987	177	97	--	anp	1
Frenchman Flat	1987	261	56	--	anp	1
Jackass Flat	1987	432	154	--	anp	1
Jackass Flat	1987	120	206	--	anp	1
Jackass Flat	1987	246	132	--	anp	1
Jackass Flat	1987	224	181	--	anp	1
Jackass Flat	1987	170	155	--	anp	1
Yucca Flat	1987	344	36	--	anp	1
Yucca Flat	1987	546	50	--	anp	1
Yucca Flat	1987	455	53	--	anp	1
Yucca Flat	1987	299	36	--	anp	1
Yucca Flat	1987	286	71	--	anp	1
Yucca Flat	1987	505	12	--	anp	1
Mid Valley	1987	842	2	--	anp	1
Mid Valley	1987	697	3	--	anp	1
Frenchman Flat	1987	--	--	378	anp	1
Frenchman Flat	1987	--	--	43	anp	1
Jackass Flat	1987	--	--	80	anp	1
Yucca Flat	1987	--	--	520	anp	1
Rock Valley	1987	--	--	175	anp	1
Mid Valley	1986	--	--	26	anp	1
Mid Valley	1987	--	--	53	anp	1
Mojave Desert	1975	124	19	51	lf	2
Mojave Desert	1976	292	96	143	lf	2
Rock Valley	1964	--	--	6	anp	3
Rock Valley	1965	--	--	0.24	anp	3
Rock Valley	1966	312	176	178	anp	3
Rock Valley	1967	195	110	45	anp	3
Rock Valley	1968	276	155	248	anp	3
Rock Valley	1971	152	89	4	anp	3
Rock Valley	1972	131	98	3	anp	3
Rock Valley	1973	440	242	644	anp	3
Rock Valley	1974	141	80	17	anp	3
Rock Valley	1975	147	63	49	anp	3
Rock Valley	1976	312	167	137	anp	3

[a] anp = annual net primary production, kg/ha; lf = litterfall, kg/ha.

[b] Citations:

1 = Hunter and Medica (1989)
2 = Strojan et al. (1979)
3 = Turner and Randall (1989)

-- indicates no data for that lifeform.

Table C-2

Litterfall and Productivity Data for Potential Future Cummunities, kg/ha (from Passey et al. 1982)

Year	Site	Litterfall					Productivity				
		annual	perennial	shrub	tree	total	annual	perennial	shrub	tree	total
1960	ID 8-60	1	160	182	--	343	1	190	217	--	408
1960	ID 9-60	28	512	349	--	889	19	345	235	--	599
1960	UT 3-58	19	889	38	--	946	26	1204	51	--	1281
1961	UT 2-58	4	801	159	115	1079	3	584	116	84	787
1961	UT 5-58	17	786	146	41	990	14	663	123	35	835
1961	ID 8-60	0	175	150	--	325	0.5	271	233	--	504
1961	ID 15-58	33	548	259	--	839	27	449	212	--	688
1961	ID 1-59	7	628	187	--	823	6	504	150	--	660
1961	ID 4-59	2	814	257	--	1072	1	520	164	--	685
1961	ID 9-60	0	446	270	--	716	0.5	321	194	--	515
1961	UT 3-58	36	888	60	--	984	28	690	47	--	765
1961	ID 6-58	12	697	99	--	809	10	563	80	--	653
1961	ID 12-58	6	455	150	--	610	5	389	128	--	522
1961	ID 13-58	14	829	283	--	1126	7	427	146	--	580
1961	ID 3-58	54	718	184	--	956	39	520	133	--	692
1962	UT 2-58	11	863	105	78	1056	16	1244	151	112	1523
1962	UT 5-58	30	611	73	28	741	47	950	113	43	1153
1962	ID 8-60	5	200	104	--	308	9	368	191	--	568
1962	ID 15-58	195	561	95	--	851	344	988	168	--	1500
1962	ID 1-59	7	871	155	--	1033	6	802	143	--	951
1962	ID 4-59	27	865	171	--	1064	24	757	150	--	931
1962	ID 9-60	13	569	245	--	827	11	481	207	--	699
1962	UT 3-58	35	390	23	--	448	81	896	53	--	1030
1962	ID 6-58	10	831	99	--	940	9	717	85	--	811
1962	ID 12-58	29	542	172	--	743	33	625	198	--	856
1962	ID 13-58	16	1134	277	--	1427	10	688	168	--	866
1962	ID 3-58	163	595	145	--	903	189	688	168	--	1045
1963	UT 2-58	6	663	107	76	853	6	617	100	71	794
1963	UT 5-58	47	789	212	63	1111	42	704	189	56	991
1963	ID 8-60	4	174	134	--	311	10	469	361	--	840
1963	ID 15-58	260	489	108	--	857	399	751	165	--	1315
1963	ID 1-59	45	691	115	--	851	57	870	145	--	1072
1963	ID 4-59	24	677	290	--	991	22	609	261	--	892
1963	ID 9-60	5	476	211	--	692	6	541	240	--	787
1963	UT 3-58	6	744	21	--	771	10	1253	36	--	1299
1963	ID 6-58	11	802	83	--	896	15	1092	113	--	1220
1963	ID 12-58	50	484	142	--	676	42	405	119	--	566
1963	ID 13-58	3	814	292	--	1109	2	554	199	--	755
1963	ID 3-58	233	551	151	--	935	317	748	205	--	1270
1964	UT 2-58	11	765	48	65	889	12	838	53	71	974
1964	UT 5-58	19	628	87	41	774	26	866	120	56	1068

Table C-2 *(Continued)*
Litterfall and Productivity Data for Potential Future Cummunities, kg/ha (from Passey et al. 1982)

		Litterfall					Productivity				
Year	Site	annual	perennial	shrub	tree	total	annual	perennial	shrub	tree	total
1964	ID 8-60	0	213	149	--	362	0.5	325	228	--	553
1964	ID 15-58	169	465	194	--	828	173	476	199	--	848
1964	ID 1-59	9	635	258	--	902	8	597	243	--	848
1964	ID 4-59	7	520	117	--	644	11	798	179	--	988
1964	ID 9-60	13	319	294	--	626	19	455	420	--	894
1964	UT 3-58	7	526	20	--	553	15	1071	40	--	1126
1964	ID 6-58	4	755	66	--	825	5	967	84	--	1056
1964	ID 12-58	45	770	83	--	898	40	688	74	--	802
1964	ID 13-58	10	752	247	--	1009	7	527	173	--	707
1964	ID 3-58	147	585	84	--	816	200	796	114	--	1119
1965	UT 2-58	6	593	426	91	1117	5	460	331	71	867
1965	UT 5-58	2	534	218	68	823	2	437	178	56	673
1965	ID 8-60	1	207	167	--	375	1	216	175	--	392
1965	ID 15-58	97	944	108	--	1149	62	605	69	--	736
1965	ID 1-59	10	912	143	--	1065	7	636	100	--	743
1965	ID 4-59	7	633	200	--	840	5	481	152	--	638
1965	ID 9-60	5	258	239	--	502	5	268	248	--	521
1965	UT 3-58	2	520	79	--	601	2	675	103	--	780
1965	ID 6-58	3	695	58	--	756	3	745	62	--	810
1965	ID 12-58	34	551	44	--	629	36	586	47	--	669
1965	ID 13-58	2	571	27	--	600	2	515	24	--	541
1965	ID 3-58	254	972	175	--	1401	200	767	138	--	1105
1966	UT 2-58	3	611	233	95	941	2	457	174	71	704
1966	UT 5-58	1	943	124	98	1167	1	538	71	56	665
1966	ID 8-60	0	185	260	--	445	0.5	130	183	--	313
1966	ID 15-58	2	684	385	--	1071	1	370	208	--	579
1966	ID 1-59	3	392	302	--	697	3	285	220	--	505
1966	ID 4-59	4	612	197	--	813	2	304	98	--	404
1966	ID 9-60	0	166	311	--	477	0.5	188	351	--	539
1966	UT 3-58	1	650	179	--	830	1	437	120	--	557
1966	ID 6-58	1	1004	252	--	1257	2.5	628	158	--	786
1966	ID 12-58	2	472	32	--	506	1	253	17	--	271
1966	ID 13-58	1	529	93	--	623	1	371	65	--	436
1966	ID 3-58	4	823	170	--	997	2	382	79	--	463
1967	UT 2-58	8	704	228	83	1024	7	593	192	70	862
1967	UT 5-58	16	605	116	45	782	20	752	144	56	972
1967	ID 8-60	0	281	217	--	498	0.5	290	224	--	514
1967	ID 15-58	117	577	260	--	954	183	898	405	--	1486
1967	ID 1-59	14	975	263	--	1252	15	1068	288	--	1371
1967	ID 4-59	22	441	471	--	934	28	556	594	--	1178
1967	ID 9-60	14	537	293	--	844	13	497	271	--	781

Table C-2 *(Concluded)*

Litterfall and Productivity Data for Potential Future Cummunities, kg/ha (from Passey et al. 1982)

Year	Site	Litterfall					Productivity				
		annual	perennial	shrub	tree	total	annual	perennial	shrub	tree	total
1967	UT 3-58	10	644	94	--	748	13	814	119	--	946
1967	ID 6-58	5	1008	146	--	1159	6	1194	173	--	1373
1967	ID 12-58	6	322	30	--	357	11	631	58	--	700
1967	ID 13-58	8	535	112	--	655	12	781	163	--	956
1967	ID 3-58	86	502	79	--	666	118	690	108	--	916
1968	ID 8-60	2	155	329	--	486	3	201	427	--	632
1968	ID 1-59	20	523	201	--	744	20	513	197	--	730
1968	ID 4-59	8	498	212	--	718	7	420	179	--	606
1968	ID 9-60	1	295	230	--	525	1	430	335	--	766
1969	ID 8-60	1	221	134	--	355	1	352	213	--	567
1969	ID 9-60	12	249	176	--	437	28	562	396	--	986

-- indicates no data for that lifeform.

Table C-3

Dependent Sample t-test Results for Tests of Differences Between Productivity and Litterfall Data, Potential Future Communities

Lifeform (community)	Number of Observations	p-value[a]
annual (shrubland)	79	0.44
perennial (shrubland)	79	0.72
shrub (shrubland)	79	0.79
total site-wide (shrubland)	79	0.62
annual (woodland)	14	0.33
perennial (woodland)	14	0.82
shrub (woodland)	14	0.18
tree (woodland)	14	0.32
total site-wide (woodland)	14	0.66
total site-wide (combined)	93	0.80

[a] Test is significant at $p < 0.05$; $p \geq 0.05$ indicates no difference between sample populations.

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APPENDIX D

SUPPORTING STATISTICAL ANALYSES

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D.1 Shapiro-Wilk and Lilliefors Goodness-of-Fit Tests

The Shapiro-Wilk and Lilliefors tests are used to evaluate whether a data set can be considered normally distributed. Lilliefors tests the maximum difference between the cumulative distributions of the data and the proposed normal distribution that is based on the data; as such, the Lilliefors test is not very sensitive to symmetry or the shape of the distribution's tails. In contrast, the Shapiro-Wilk test uses a test statistic that is sensitive to the symmetry of the data and the shape of the distribution's tails. Generally, the Shapiro-Wilk test is less likely than the Lilliefors test to accept a data set as normal.

Both the Shapiro-Wilk and Lilliefors normality tests assume the data are normally distributed. Each returns a statistic that tests the validity of this assumption. The test statistic returned is relatively small if the data set is not normally distributed. Relatively large values for the test statistic are returned when there is insufficient evidence to conclude that the data were not obtained from a normal distribution, i.e., the data set can be considered normal. In addition to the test statistic, each test computes the probability (p-value) of finding a value less than the computed test statistic from normally distributed data. If this probability is less than some determined level of significance (usually $\alpha = 0.05$), then the assumption of normality can be rejected with a level of confidence equal to $1-\alpha$ (e.g., 95 percent confidence when $\alpha = 0.05$). Likewise, if this probability is greater than α, then the assumption of normality is accepted.

When the tests are performed on log-transformed data, the assumption of lognormality is tested. A probability less than α is sufficient to reject the data as lognormal. For a probability greater than α, the data can be accepted as being lognormally distributed.

In cases where a data set fails the tests at the $\alpha = 0.05$ significance level, a measured probability between 0.001 and 0.05 is often good enough to indicate the data still closely approximate a normal (or lognormal) distribution.

D.2 Cross-Correlation Analysis

Cross-correlation estimates the correlation between one time series at time t and a second time series at time t-k as a function of the lag or time differential k. At t=0, the time series overlap completely and with each successive increment of k, the time series have one less pair of overlapping numbers. Some requirements of the analysis include: each data set must have the same number of observations; observations for paired data sets must have been taken at the same time periods; the lag lengths used in the analysis must not exceed one half of the length of the data series for meaningful results; and lastly, each data set must be stationary, lacking predictable or systematic changes in the mean through time.

With total litterfall as one time series, total productivity as the other series, and k in units of years, the data for each site were analyzed to determine whether total litterfall was correlated to total productivity measured within a particular year and for each of the preceding years for which there were data. Lag lengths varied from zero to four, depending on the site and number of years for which there were data. The stationarity requirement was met for all the data sets.

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