NAC-0013_R1

Biotically-Induced Contaminant Transport Modeling for the WCS Site Model v0.205

20 November 2013

Prepared for Waste Control Specialists, LLC, by

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</table>

CONTENTS

FIGURES

TABLES

1.0 Overview

At its disposal site in Andrews County, Texas, Waste Control Specialists, LLC, (WCS) has constructed two disposal units for low-level radioactive waste (LLW). In 2007, WCS submitted their *Application for License to Authorize Near-Surface Land Disposal of Low-Level Radioactive Waste* (WCS, 2007) to the TCEQ. In April of 2012, WCS began waste disposal activities. A Performance Assessment (PA) of the disposal facility was included as a component of the license application in order to fulfill requirements under Subchapter H of TAC Title 30 Chapter 336 to provide sufficient technical and environmental analyses to demonstrate that the facility will meet the applicable performance objectives. The refinement of this initial PA to address site-specific biotically-induced contaminant transport pathways in a probabilistic manner is the subject of this paper. The WCS Site Model is developed in support of the PA.

2.0 Parameter Values Summary

Individual model parameters and associated input values used in the biological contaminant transport modeling at the WCS Site Model are identified in the *WCS Site Model Parameters.docx*. In this document, a more comprehensive record for each parameter is provided, including the source of the values and notes explaining the basis.

For distributions, the following notation is used:

- N(μ, σ, [*min*, *max*]) represents a normal distribution with mean μ and standard deviation σ, and optional truncation at the specified *min*imum and *max*imum, and
- gamma(μ, σ, *min*, *max*) represents a gamma distribution with mean μ and standard deviation σ, also truncated at *min*imum and *max*imum.

The term ‘Small’ used in some distributions refers to a very small, positive value. The term ‘Large’ used in some distributions refers to a very large, positive value. These values are defined in the WCS Site Model.

A summary of the values and probabilistic distributions used in the WCS Site Model is provided in Table 1.

Table 1. Summary of biotic input distributions for the WCS Site Model

parameter name	value or distribution	units	comments / references
	Plant Transport Parameters		
above-ground biomass primary production rate	N(305, 27.67, Small, Large)	$g/m^2 \cdot yr$	See Section 3.3
plant/soil concentration ratios	tabulated in the companion workbook *WCS Site Model Parameters.xlsx*	—	see *NUREGCR-5512 Tables.xlsx*; discussion in Section 3.6
mesquite: root:shoot ratio	N(0.6731, 0.05, Small, Large)	—	See Section 3.4
mesquite: maximum root depth	1000	cm	See Section 3.5
mesquite: root shape parameter *b*	N(25, 0.5, 1, Large)	—	See Section 3.5
grasses: root:shoot ratio	N(1.11, 0.175, Small, Large)	—	See Section 3.4
grasses: maximum root depth	60	cm	See Section 3.5
grasses: root shape parameter *b*	N(6, 0.12, 1, Large)	—	See Section 3.5
forbs: root:shoot ratio	N(0.59, 0.192, Small, Large)	—	See Section 3.4
forbs: maximum root depth	55	cm	See Section 3.5
forbs: root shape parameter *b*	N(23.9, 0.466, 1, Large)	—	See Section 3.5
shrubs: root:shoot ratio	N(0.6731, 0.25, Small, Large)	—	See Section 3.4
shrubs: maximum root depth	60	cm	See Section 3.5
shrubs: root shape parameter *b*	N(2, 0.04, 1, Large)	—	See Section 3.5
	Mammal Transport Parameters		
area density of mammal mounds on the ground	gamma(77.5, 5.08, 0, Large)	1/ha	See Section 4.5
below-ground volume of a single burrow excavation	N(0.1185, 0.025, Small, Large)	m^3	See Section 4.3
fraction of burrow renewed in a year	N(0.20, 0.05, 0, 1)	1/yr	See Section 4.3
burrow shape parameter *b*	N(4.5, 0.84, 1, Large)	—	See Section 4.6
maximum depth of all burrows	427	cm	See Section 4.4
	Ant Transport Parameters		
area density of ant colonies (nests) on the ground	gamma(14.36, 1.094, 0, Large)	1/ha	See Section 5.7
below-ground volume of a single nest	N(0.64, 0.091, 0, Large)	m^3	See Section 5.3
lifespan of an ant nest	N(20.2, 3.6, Small, Large)	yr	See Section 5.5
ant nest shape parameter *b*	N(10, 0.71, 1, Large)	—	See Section 5.6
maximum depth of ant nest	400	cm	See Section 5.4

3.0 Plant Specifications and Parameters

The purpose of this chapter is to explain the component of the WCS Site Model that addresses calculation of plant-mediated contaminant mass distributions by depth, and the rate of contaminant transport from subsurface strata to the ground surface.

3.1 Plant Conceptual Model

Plant-induced transport of contaminants is assumed to proceed by absorption of contaminants into plant roots, followed by redistribution throughout all the tissues of the plant, both above ground and below ground. Upon senescence, the above-ground plant parts are incorporated into surface soils, and the roots are incorporated into soils at their respective depths (Figure 1), returning contaminants to the adjacent soils.

The calculations of contaminant transport due to plant uptake and redistribution take place in a series of steps:

1. Calculate the fraction of plant roots in each layer for each plant type.
2. Calculate uptake of contaminants into plant roots in each layer.
3. Sum the contaminant uptake to determine the total uptake by the roots for each contaminant.
4. Determine the average concentration in the roots, assuming complete redistribution within the root mass.
5. Assuming that the plant returns all fixed contaminants to adjacent soils upon senescence, determine how much of each contaminant is returned to each layer. The above-ground plant parts are mixed in the uppermost layer.
6. Calculate uptake of contaminants into above-ground parts of the plant (the "shoots"), based on the fractions of roots fixing contaminants within each layer and sending it up to the shoots.
7. Calculate the net flux of contaminants into (or out of) each layer due to steps 1 through 6. This value is used to adjust contaminant inventories in each layer (each layer is a GoldSim cell).

This section describes the functional factors that contribute to the parameterization of the plant section of the biotic transport model. Such factors include identifying dominant plant species, grouping plant species into categories that are significantly similar in form and function with respect to the transport processes, estimating net annual primary productivity (NAPP, a measure of above-ground biomass generation), determining relative abundance of plants or plant groups, evaluating root/shoot mass ratios, and representing the density of plant roots as a function of depth below the ground surface. The data used for each of the seven steps of the algorithm are presented, outstanding issues with the available data are identified, and the issues that deserve attention for the next model iteration are described.

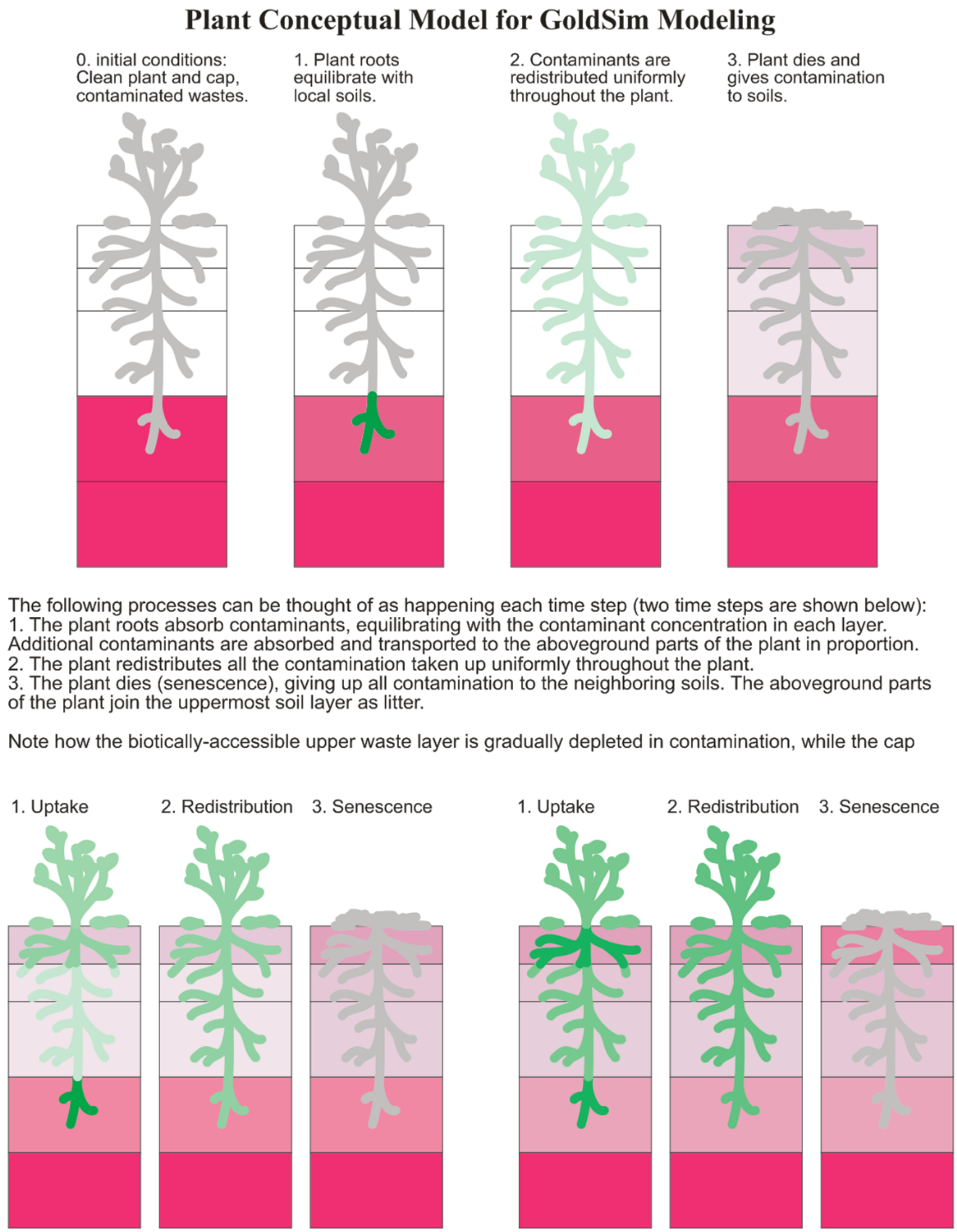


Figure 1. Conceptual model of contaminant uptake and redistribution by plants

In the WCS Site Model, the vertical soil column is discretized into horizontal layers based on the configuration of the disposal cell cover. The plant model is ultimately used to calculate the contribution by plants to radionuclide transport throughout the soil layers. Utilizing the information provided in steps 1 through 6 above, distributions of above-ground and below-ground NAPP for mesquite, grasses, forbs, and other shrubs are developed. Radionuclide activity associated with above-ground biomass is assigned to the uppermost soil/cover layer in the model. Radionuclide activity associated with below-ground NAPP is apportioned by depth interval according to root mass distribution. In order to reflect the redistribution of radionuclides, these calculations require the use of plant uptake factors (plant-soil concentration ratios) to model the relative uptake of contaminants from soil by plants.

3.2 Identification of Plant Functional Groups

A representative species list for the WCS site was taken from Appendix 2.9.1 *Ecological Assessment* of the License Application (WCS, 2007), in Attachment 1A: *Habitat Characterization and Rare Species Survey for the Proposed Low Level Waste Repository, Andrews County, Texas* (Reagan and Associates 2004). Shrubs and grasses are the dominant vegetation within 5 km of the site. Dominant species were recorded in 18 plots. A total of 27 plant species were identified in this dominant list. These species are categorized into the four functional groups: mesquite, forbs, grasses, and other shrubs. Mesquite is separated from other shrubs due to its distinct ability to extend deep taproots. See Table 2 for species identified in the 2004 survey.

Table 2. Plant species identified at the WCS Site

Plant Group	Common Name	Species Name
mesquite	Mesquite	*Prosopis glandulosa*
forb	Western ragweed	*Ambrosia psilostachya*
forb	Loco weed	*Astragalus sp.*
forb	Lambsquarter	*Chenopodium sp.*
forb	Thistle	*Cirsium sp.*
forb	Fleabane	*Erigeron spp.*
forb	Annual buckwheat	*Eriogonum annuum*
forb	Snakeweed (perennial broomweed)	*Gutierrizia sarothrae*
forb	Primrose	*Oenothera sp.*
forb	Russian thistle	*Salsola iberica*
forb	Groundsel	*Scenico longilobus*
forb	Silverleaf nightshade	*Solanum eliagnifolium*
forb	Globe mallow	*Sphaeralcea coccinea*
forb	Annual broomweed	*Xanthocephalum dracunculoides*
grass	Sand bluestem	*Andropogon hallii*
grass	Purple three-awn	*Aristida purpurea*
grass	Black grama	*Bouteloua eriopoda*
grass	Blue grama	*Bouteloua gracilis*
grass	Buffalo grass	*Buchloe dactyloides*

Plant Group	Common Name	Species Name
grass	Muhly	*Muhlenbergia sp.*
grass	Little bluestem	*Schizachyrium scoparium*
grass	Sand dropseed	*Sporobolus cryptandrus*
shrub	Sand sagebrush	*Artemisia filifolia*
shrub	Rabbitbrush	*Chrysothamnus pulchellus*
shrub	Prickly pear cactus	*Opuntia sp.*
shrub	Shinnery oak	*Quercus havardii*
shrub	Soapweed	*Yucca sp.*

3.3 Estimation of Net Annual Primary Production

Net annual primary productivity has not been measured at the WCS site or in the adjacent vegetative associations. Biomass production rate is estimated from plot measurements in three different mesquite habitat types (upland clusters, upland groves, and lowland woodlands) using foliar estimates (Hibbard et al., 2001). The representation of the site for a 10,000-year period (i.e. without consideration for climate change) is considered an average of these three types. A normal distribution was applied, with the mean and standard deviation equal to the sample mean and sample standard deviation of these three types (mean = 305 $g/m^2 \cdot yr$ and SD = 27.67 $g/m^2 \cdot yr$).

A total biomass production for the selected plot is drawn from this distribution. Since these data are not on a per-plant or per-species basis, percent cover of each plant group is used to apportion NAPP by vegetation type. This biomass is then apportioned based on the percent of vegetation from each plant type.

Reagan and Associates (2004) provide the best site-specific information on plant life, and identify the representative species list for the WCS site. In order to inform the estimation of primary productivity, which depends on abundance of species, the published literature was searched for information regarding plant cover in mesquite communities. Values used were taken directly from the literature. Plant cover varies greatly among plots and sites. For the purposes of this model, remote sensing is the best source of typical plant cover to use for this site in the absence of site-specific abundance data. Remote sensing data for a mesquite community in Texas for both 1-m and 30-m resolution imagery was used from Mirik and Ansley (2012). Since mesquite canopy and grass patches are smaller than the pixel size for the 30-m imagery (Mirik and Ansley 2012), the 1-m image data was used for the purposes of estimating plant cover for this model.

The values from the 1-m image data were used to estimate the vector probabilities associated with a multinomial distribution as (0.10, 0.76, 0.07, 0.07) corresponding to the vegetation types mesquite, grass, forb, and other shrub, respectively. Using this vector, one thousand random sets from this multinomial distribution were generated and exported into a table that is built into the WCS Site Model. Since the 1000 sets are of equal probability, one is chosen at random for each

realization in the model. The biomass production rate was then partitioned among the percent cover for the plant functional types described by this distribution.

3.4 Root:Shoot Ratios

The root:shoot ratio is the ratio of biomass below-ground to that above-ground for a particular plant type. For example, a value of 0.67 means that the biomass of roots is about 2/3 that of the above-ground plant parts. Using the representative species list for the WCS site from Reagan and Associates (2004), the published literature was searched for any information regarding root:shoot ratios of the dominant species present at the WCS site. Values were taken directly from the literature or calculated from published values of above- and below-ground biomass in the same study. Values for individual species in each plant functional type were averaged to create distributions used in the model, shown in Table 3. No data were found for other shrub species on the WCS site list, so mesquite values were used to represent other shrubs.

Table 3. Root:shoot ratios by plant group

Plant Group	Distribution	References
Mesquite	N(0.6731, 0.05, Small, Large)	Perkins and Owens 2003, estimated from non-defoliated samples in Figure 1
Grass	N(1.11, 0.175, Small, Large)	Based on Engel et al. 1998, Perkins and Owens 2003, Peters 2002, Qian et al. 1997, Marcum et al. 1995, Dhillion 1999, Grant et al. 2003
Forb	N(0.59, 0.192, Small, Large)	Based on Maganti et al. 2005, Borjigidai et al. 2009, Peters 2002, Travlos 2013
Other shrub	N(0.6731, 0.05, Small, Large)	Based on mesquite since no data were found for other shrub species on WCS list

3.5 Maximum Root Depths and Biomass Shape

The geometrical distribution of the root mass is important in determining which layers of the soil column are tapped by roots, and to what degree. The virtual root biomass shape for all plants within a particular functional group is modeled with two parameters: the maximum depth, and a shape parameter *b* that defines a range of shapes, from a cylinder to a cone to a “tornado” shape that has a distinct tap root.

Using the representative species list for the WCS site from Reagan and Associates (2004), the published literature was searched for any information regarding root distributions by soil depth. Values used were taken directly from the literature. This information can be used to develop the *b* shape parameter. This shape is dependent on a flexible functional form the equation for which is shown below. This shape also generates the estimate of the maximum root depth used in the model. The mesquite root depth was adjusted to account for the commonly found deep roots. Mesquite roots are commonly known to reach depths of 1200 cm (Steinberg, 2001), but this is limited by certain conditions. The United States Forest Service (USFS) discusses such conditions in its documentation of botanical and ecological characteristics of honey mesquite:

> "In areas where the soil is shallow, where water does not penetrate deeply, or where a distinct calcium carbonate layer is present, the taproot seldom extends more than 3 to 6 feet (1-2 m)..."

(Steinberg, 2001, available at http://www.fs.fed.us/database/feis/plants/tree/progla/all.html)

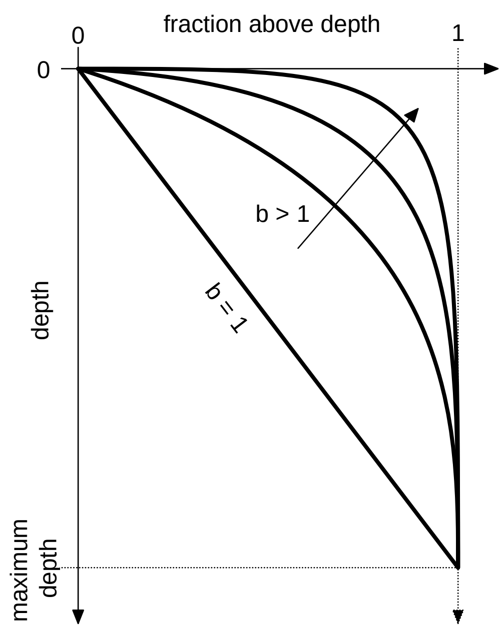
At the WCS site, all these conditions are present, and the maximum root depth is adjusted to a maximum possible root depth of 10 m due to a concrete layer modeled at 11 m below ground surface. Concrete in this instance serves as a source of calcium carbonate, much like the naturally occurring local caliche.

The function f_i used to represent root densities actually defines the fraction of all roots above any given depth. At depth $z = 0$, the value is 0 by definition, and at the maximum root depth, where $z = z_i^{max}$, the value is 1, meaning that all roots are above that depth (the definition of maximum root depth). The fraction of roots for plant *i* above any depth *z* is

$$f_i^z = 1 - \left(1 - \frac{z}{z_i^{max}}\right)^{b_i} \quad \textbf{(1)}$$

where

f_i^z	fraction of roots for plant *i* above any depth *z*,
z_i^{max}	maximum rooting depth for plant *i*, and
b_i	fitting parameter for the root density equation, for plant *i*.



A value of *b* = 1 indicates a uniform cylindrical "can-shape" distribution of roots from the surface to maximum rooting depth. Increasing *b* values result in a narrowing of overall rooting width with depth, with *b* = 3 resulting in a "cone-shaped" distribution of roots, and *b* values greater than 4 indicating increasingly "funnel-shaped" distributions with depth, as might be found in plants producing taproots.

Maximum depths and root shape *b* parameters for plants found at the WCS site are provided in Table 4.

Table 4. Maximum root depth and *b* shape parameter by plant group

Plant Group	*b* shape parameter	maximum root depth (cm)	References
Mesquite	N(25, 0.5, 1, Large)	1000	Based on Moore et al. 2010, Table 2 Control Plots with root depth adjusted from Steinberg (2001)
Grass	N(6, 0.12, 1, Large)	60	Estimate from Kurc and Small (2004)
Forb	N(23.9, 0.466, 1, Large)	55	Estimated form Clive Data
Other shrub	N(2, 0.04, 1, Large)	60	Estimated from Kurc and Small (2004)

3.6 Estimation of Plant Uptake of Radionuclides

Radionuclide concentrations in plant tissues are calculated based on root uptake using plant/soil concentration ratios (*CR*), expressed as activity per dry weight plant tissue divided by activity per dry weight of bulk soil (Bq/g dry plant per Bq/g dry soil). Radioelement-specific *CR* values were obtained from NUREG/CR-5512 (NRC, 1992), and were used in previous WCS modeling. These values are tabulated in the workbook *WCS Site Model Parameters.xlsx*, which is linked electronically to the workbook *NUREGCR-5512 Tables.xlsx*.

Plant/soil concentration ratios reflect an assumption that there is a linear and unchanging relationship between soil and plant tissue concentrations. These assumptions may overestimate plant tissue concentrations as soil concentrations increase to levels higher than those employed in the studies from which the values are derived. This may apply in the WCS Site Model to conditions where plant roots are in contact with elevated uranium or technetium concentrations, as might be present in some candidate waste streams. The WCS Site Model assumes that plant roots are in contact with soils in various layers below-ground, each of which has its own concentration of contaminants (radionuclide “Species” in GoldSim parlance). The roots present in each layer absorb each Species proportionally to the concentration of that Species in the soil in that layer. These absorbed Species are distributed uniformly throughout all the plant’s tissues, above-ground and below-ground. The plant is then assumed to die off, and all the Species contained within it are returned to soils in each layer according to the fraction of roots present in that layer. Above-ground plant parts are returned to the topmost soil layer. All of these processes take place in a single time step, and are integrated with other contaminant fate and transport processes such as resuspension into the atmosphere, diffusion in pore air and water, and radioactive decay and ingrowth. Details on these calculations follow.

The concentration of Species *j* in the plant *i* with roots in layer *N* is simply

$$C_{i,j}^{N} = CR_j \cdot C_s^N \,. \qquad \textbf{(2)}$$

where

$C_{i,j}^{N}$ concentration of Species *j* in plant *i* roots in layer *N,*

CR_j concentration ratio for all plants and Species *j*, and

C_s^N concentration in soil on layer *N*.

The total mass of Species *j* extracted by roots of plant *i* from soils (or wastes) in layer *N* is

$$M_{i,j}^{N} = C_{i,j}^{N} \cdot MP_i \cdot f_i^{N} \cdot f_{root} + C_{i,j}^{N} \cdot MP_i \cdot f_i^{N} \cdot f_{shoot} \quad \textbf{(3)}$$

where

f_i^{root} mass fraction of plant *i* that is in the roots (below-ground fraction),

f_i^N mass fraction of root of plant *i* that is in layer *N* (so that the fraction of the entire plant in layer *N* is $f_i^{root} \times f_i^N$),

f_i^{shoot} mass fraction of plant *i* that is in the shoots (above-ground fraction),

$M_{i,j}^N$ mass of Species *j* extracted by the roots of plant *i* in layer *N* , and

MP_i mass of all individuals of plant *i* over the site (M).

The model assumes that all absorbed Species are distributed uniformly throughout all the plant tissues, both above-ground parts and roots. The total mass of Species *j* in plant *i* is the total mass extracted by the roots of the plant summed across all *N* layers:

$$M_{i,j}^{T} = \sum_{N} M_{i,j}^{N} . \quad \textbf{(4)}$$

where

$M_{i,j}^T$ total mass of Species *j* extracted by the roots of plant *i* and redistributed throughout the plant tissues, and

$M_{i,j}^N$ mass of Species *j* extracted by the roots of plant *i* in layer *N*.

This total amount of Species mass is divided up into the parts of the plant that occupy each layer, as well as the above-ground parts, so that we may calculate the mass of contamination ${}^{+}M_{i,j}^{N}$ that the plant returns to the various soil layers upon senescence. The total amount of contamination returned to the soils must equal the amount that was absorbed (not accounting for decay of the Species), in order to conserve mass of the Species. This total absorbed Species mass is returned to the soil in proportion to the amount of plant in each layer, with the topmost soil layer also receiving the above-ground plant parts:

$$
\begin{aligned}
{}^{+}M_{i,j}^{1} &= M_{i,j}^{T} \cdot f_{root} \cdot f_{i}^{1} + M_{i,j}^{T} \cdot f_{shoot} \\
{}^{+}M_{i,j}^{2} &= M_{i,j}^{T} \cdot f_{root} \cdot f_{i}^{2} \\
&\vdots \\
{}^{+}M_{i,j}^{N} &= M_{i,j}^{T} \cdot f_{root} \cdot f_{i}^{N}
\end{aligned} \tag{5}
$$

The net mass added to each layer is the redistributed mass from Equation 5 minus the absorbed mass from Equation 3. For plant *i*, this net mass added is simply

$$
{}^{+}M_{i,j}^{N} - M_{i,j}^{N}. \tag{6}
$$

The GoldSim model contains various plant types. For the sake of simplicity in defining changes to each cell's inventory, the Species redistribution for all plants can be combined to result in a net addition (or subtraction) of mass effected by all plants. To do so, we sum Equation 6 over all the plant types:

$$
{}^{+}M_{j}^{N} = \sum_{i} {}^{+}M_{i,j}^{N} \quad \text{and} \quad M_{j}^{N} = \sum_{i} M_{i,j}^{N}. \tag{7}
$$

4.0 Mammal Specifications and Parameters

4.1 Mammal Conceptual Model

Burrowing mammals can have an important effect on the distribution of soil and its contents near the soil surface. The degree to which mammals influence soil structure is dependent on the behavioral habits of individual species. While some species account for a large volume of soil displacement, others are less influential. This section presents the functional factors used to parameterize the WCS Site Model. Factors such as burrowing depth, burrow depth distributions, percent burrow by depth, soil displacement by volume and burrow density per hectare play a role in determining the final soil constituent mass by depth within the soil.

Modeling soil and contaminant transport by mammal species within the WCS Site Model assumes that animals move materials from lower cells to the ground surface while excavating burrows. Furthermore, burrows are assumed to collapse over time and return soil from upper cells back to lower cells (Figure 2). Thus, the balance of

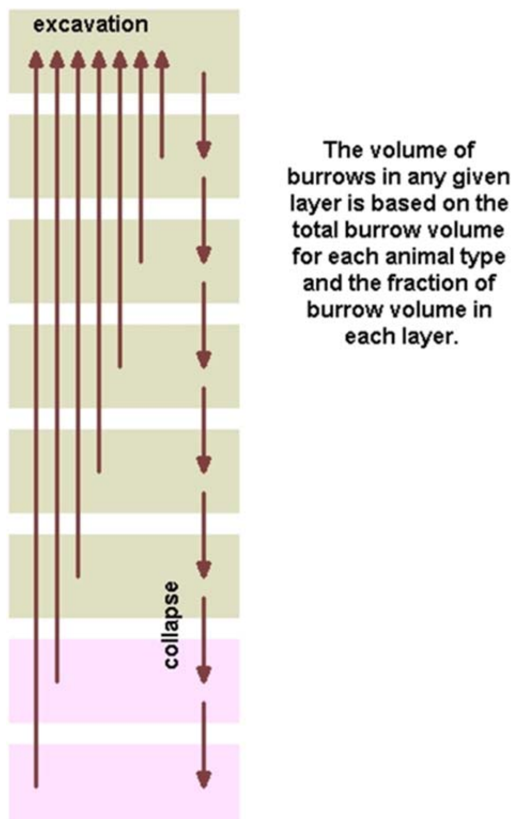


Figure 2. Conceptual diagram of soil movement by burrowing animals

materials is preserved through time. Calculating soil and contaminant movement from one cell to another is straightforward. Within each layer, the fraction of burrow volume and the fraction of contaminants contained within the burrowed volume are determined. The fraction of contaminants within the burrowed volume is based on the ratio of burrow volume to total volume of each layer and is assumed to be distributed homogeneously within each layer. Secondly, the sum of contaminants from each layer associated with burrow excavation by all animal types is calculated with the assumption that all excavations from layers below are deposited in the uppermost layer. Finally, downward movement of contaminants associated with burrow collapse from each layer to the layer below is calculated and the net movement of contaminants into each layer is determined. The amount of contaminants in each layer is then used to adjust contaminant inventory in each layer for the next time step.

The calculations of contaminant transport due to mammal burrowing involves four steps:

1. Identify which of the mammal species potentially contribute to the rearrangement of soils near the surface.
2. Determine the excavated volumes for selected mammal species.
3. Calculate burrow density as a function of depth for mammal categories.
4. Determine the distribution of the burrow depth fitting parameter *b* for mammal categories. This parameter is analogous to the one defined for plants discussed in Section 3.5.

4.2 Identification of Mammals Species Potentially Important to Soil Movement at WCS

Representative fossorial (burrowing) mammal species for WCS were selected based on review of the following information sources: 1) Attachments 1 and 2 from Appendix 2.9.1 *Ecological Assessment* for the WCS License Application (WCS, 2007), and 2) range maps for fossorial species groups (prairie dogs, ground squirrels, pocket gophers, pocket mice, kangaroo rats) presented in *The Mammals of Texas, Online Edition* (Davis and Schmidly, 1997). A number of burrowing mammal species have been observed at WCS, including Mexican ground squirrel, Ord's kangaroo rat, silky pocket mouse, hispid pocket mouse, and Merriam's pocket mouse. The *Ecological Assessment* for WCS notes that black-tailed prairie dogs have not been recorded from WCS or Andrews County, but occur in all surrounding counties, and are therefore included as a representative species for evaluation of soil movement by biota at WCS.

4.3 Mound Volume

Measures of mammal mound volume are used as an estimator of the amount of soil excavated by burrowing mammals on an annual basis. The volume of soil excavated on an annual basis was calculated based on literature reports. If a reference did not directly report the volume of soil present in a mound, the amount of excavated soil was calculated from reported burrow dimensions. The amount of excavated soil per burrow was calculated as volume of a cylinder, where burrow length is the cylinder length, and radius equals half the diameter of the burrow. Excavated burrow volumes for representative mammal species at WCS are shown in Table 5. After evaluation of available data, derivation of the mound volume distribution was limited to data for Black-tailed Prairie Dog (*Cynomys ludoviscianus*). This choice is largely driven by the

dominance of this species for the maximum burrow depth among all burrowing animals potentially occurring at the site. Based on analysis of the data presented in Table 5, the per-burrow excavated volume is defined as a normal distribution with a mean of 0.1185 m^3, and a standard deviation of 0.025 m^3. This distribution is truncated just above zero in order to prevent negative values and divide-by-zero errors. The total excavated volume is equal to the individual burrow volume multiplied by the burrow density. Since prairie dog colonies are long-lived, often persisting for decades, professional judgment was used to assume that 20% of total colony burrows are re-excavated or newly excavated on an annual basis. This is given a normal distribution using 0.20 as the mean, 0.05 as a standard deviation, and is truncated at the theoretical limits of 0 and 1 for a fraction.

Table 5. Excavated mammal burrow volumes for representative mammals in West Texas

Species	Burrow Length (m)	Burrow Diameter (m)	Excavated Burrow Volume (m^3 per burrow)	Citation	Notes
Black-tailed Prairie Dog (*Cynomys ludoviscianus*)	8.5	0.10	0.067	Davis and Schmidly, 1997	
	16		0.17	Long, 2002	Avg Burrow volume reported in reference.
Mexican Ground Squirrel (*Spermophilus mexicanus*)	4.5	0.0825	0.024	Edwards, 1946	Burrow length estimated from total length of excavated tunnels illustrated in lower right of Figure 1-4 in Edwards.
Spotted Ground Squirrel (*Spermophilus spilosoma*)	4	0.05	0.008	Davis and Schmidly, 1997	
Thirteen-Lined Ground Squirrel (*Spermophilus tridecemlineatus*)	7	0.05	0.014	Davis and Schmidly, 1997	
	1.1	0.05	0.0022	Desha, 1966, Davis and Schmidly, 1997	Burrow length calc based on Desha, 1966. Burrow diameter from Texas Tech Univ, 1997.
Jones Pocket Gopher (*Geomys knoxjonesi*)	>100	0.06	0.28	Davis and Schmidly, 1997	Avg reported mound volume of 0.01 m3, max reported mound volume of 1.8 m3
Silky Pocket Mouse (*Perognathus flavus*)	1	0.025	0.0005	Davis and Schmidly, 1997	Burrow diameter based on Hispid Pocket Mouse from same reference
Merriam's Pocket Mouse	1.35	0.025	0.0007	Davis and Schmidly, 1997	Burrow diameter based on Hispid Cotton Mouse from same reference

Species	Burrow Length (m)	Burrow Diameter (m)	Excavated Burrow Volume (m^3 per burrow)	Citation	Notes
Texas Kangaroo Rat (*Dipodomys elator*)	2.5	0.09	0.016	Carter et al, 1985	Burrow diameter based on Ord's Kangaroo Rat
Merriam's Kangaroo Rat (*Dipodomys merriami*)	Avg = 3.6 m	0.09	0.022	Bienek and Grundmann, 1971	Burrow diameter based on Ord's Kangaroo Rat
Ord's Kangaroo Rat (*Dipodomys ordii*)			0.008 ± 0.009	Laundré and Reynolds, 1993	Reported mean volume (± SD) from 17 excavations
	1.3 – 5.4	0.085 – 0.09	0.008 – 0.033	White, 2009	Ranges based on 9 burrow excavations
American Badger	1.5	0.2	0.05	Andersen and Johns (1977); Davis and Schmidly, (1997)	Length form Andersen and Johns (1977); diameter from Davis and Schmidly (1997)

4.4 Maximum Burrow Depth

Maximum burrow depths for representative mammal species were obtained from published literature. A summary of the reported burrow depths for species potentially occurring at WCS is presented in Table 6. The WCS Site Model uses depth as a scalar value, therefore maximum depth is represented by a single value instead of a distribution. Burrow depths for black-tailed prairie dog were selected since these are the deepest burrowers that occur in West Texas. Maximum burrow depth is represented in the model as 4.27 m based on reported burrow depths for black-tailed prairie dog.

Table 6. Maximum mammal burrow depths for representative mammals in West Texas

Species	Max Burrow Depth (m)	Citation	Notes
Black-tailed Prairie Dog (*Cynomys ludoviscianus*)	2.0 to 5.0	Davis and Schmidly , 1997	
	0.91 to *4.27*	Sheets et al. 1971	Range based on 18 excavated burrows
	1.8	Van Vuren and Ordeñana, 2012, Table 1	Reported avg of 29 studies
Thirteen-lined Ground Squirrel (*Spermophilus tridecemlineatus*)	1.15	Davis and Schmidly, 1997	
	0.24 mean 0.4 max	Desha, 1966	Reported mean and max depth of 14 nesting burrows excavated

Mexican Ground Squirrel (*Spermophilus mexicanus*)	1.27	Edwards, 1946	Reported max depth of 50 burrows excavated
Spotted Ground Squirrel (*Spermophilus spilosoma*)	0.5	Davis and Schmidly, 1997	
Jones Pocket Gopher (*Geomys knoxjonesi*)	0.675	Davis and Schmidly , 1997	Reported Max depth of 40 burrows excavated for Plains Pocket Gopher. Jones Pocket Gopher is part of a cryptic species complex with Plains Pocket Gopher.
Silky Pocket Mouse (*Perognathus flavus*)	0.10	Davis and Schmidly , 1997	
Hispid Pocket Mouse (*Chaetodipus hispidus*)	0.4	Davis and Schmidly , 1997	
Merriam's Kangaroo Rat (*Dipodomys merriami*)	0.75 to 1.63	Bienek and Grundmann, 1971	Range based on 5 nests excavated
Texas Kangaroo Rat (*Dipodomys elator*)	0.45	Carter et al., 1985	
Ord's Kangaroo Rat (*Dipodomys ordii*)	0.35 to 0.65	White, 2009	Range based on 8 excavations
	0.41 ± 0.196	Laundré and Reynolds, 1993	Based on 17 excavations
American Badger	1.5	Andersen and Johns, 1977	Burrow depth excavated by a badger in 25 minutes to reach a yellow-bellied marmot

4.5 Mammal Burrow Area Density

A distribution of mammal densities was derived from literature-reported densities for the representative mammal species for the site. A summary of literature reported mammal densities is presented in Table 7. The reported values are based on the number of burrows per hectare as opposed to number of individual animals per hectare, since individuals of many species excavate and maintain multiple burrows over the course of a year.

The literature review of fossorial mammal activity in the region in and around the WCS site suggests that black-tailed prairie dog, *Cynomys ludoviscianus*, is considered to be the dominant mammal in the region with respect to burrowing characteristics, particularly with regard to burrowing depth, and size and longevity of colonies. Consequently, mammal-burrowing activity is being characterized using data from this single species. Using data from Table 7, the prior distributions are updated. Where ranges of data are presented in the literature, each value of the range is considered as a single observation in this context. This interpretation of the literature is conservative in the sense that it reflects a high level of uncertainty. Given the parameterization of the gamma distribution in the statistical software *R*, it is convenient to provide the mean and

standard deviation in order to parameterize this distribution in GoldSim. Hence, the distribution used to inform GoldSim is

gamma(mean = 77.50, standard deviation = 5.08), truncated at 0 and Large.

Table 7. Burrow density of representative mammal species potentially occurring at the WCS Site

Species	Max Burrow Density (1/ha)	Citation	Notes
Black-tailed Prairie Dog (*Cynomys ludoviscianus)*	39 – 66 burrows/ha	Long, 2002, Sheets et al, 1971	Based on range of 75 – 125 entrances/ha from Long, and avg of 1.9 entrances per burrow from Sheets et al.
	127 burrows/ha	Hoogland, et al, 1987, Sheets et al, 1971	Based on reported 241 entrances/ha (Hoogland et al), and an average of 1.9 entrances per burrow from Sheets, et al.
Thirteen-lined Ground Squirrel (*Spermophilus tridecemlineatus*)	70.1 burrows/ha	Desha, 1966	Based on reported 245 burrow entrances over 2.24 ha, with avg of 1.56 entrances/burrow
Mexican Ground Squirrel (*Spermophilus mexicanus*)	No Information found		
Spotted Ground Squirrel (*Spermophilus spilosoma*)	9 – 31.5 burrows/ha (Oklahoma) 17.1 burrows/ha (Colorado)	Streubel and Fitzgerald, 1978	Assumes ground squirrel burrow density = 4.5 x animal density based on *S. tridecemlineatus,* from Desha, 1966,
Jones Pocket Gopher (*Geomys knoxjonesi*) (Considered part of cryptic species complex with Plains Pocket Gopher)	3.2 burrows/ha (avg), 17.6 burrows/ha (max)	Davis and Schmidly, 1997	Reported avg and max density for Plains Pocket Gopher in Texas. Assumes burrow density = animal density
Silky Pocket Mouse (*Perognathus flavus*)	No information found		
Hispid Pocket Mouse (*Chaetodipus hispidus*)	No information found		
Merriam's Kangaroo Rat (*Dipodomys merriami*)	0.3 to 3.7 (Mojave desert) 18.5 (Creosote scrub) 2.6 (Pinyon – Juniper) 13 to 19 (Creosote scrub)	California Dept. Fish and Game, 1999	Assume burrow density = animal density
Texas Kangaroo Rat (*Dipodomys elator*)	8.6 to 24.7 burrows/ha	Carter et al, 1985	Assume burrow density = animal density
Ord's Kangaroo Rat (*Dipodomys ordii*)	11.3/ha (Great Basin) 2.8/ha (salt desert) 13.5/ha (greasewood)	Sullivan, 1995	Assume burrow density = animal density

Species	Max Burrow Density (1/ha)	Citation	Notes
American Badger	3.65 burrows/ha/yr	Idaho State University, 2000	Assumes density of 1 badger per 100 ha (professional judgment), and badger digging new burrow every day (Idaho State Univ, 2000)

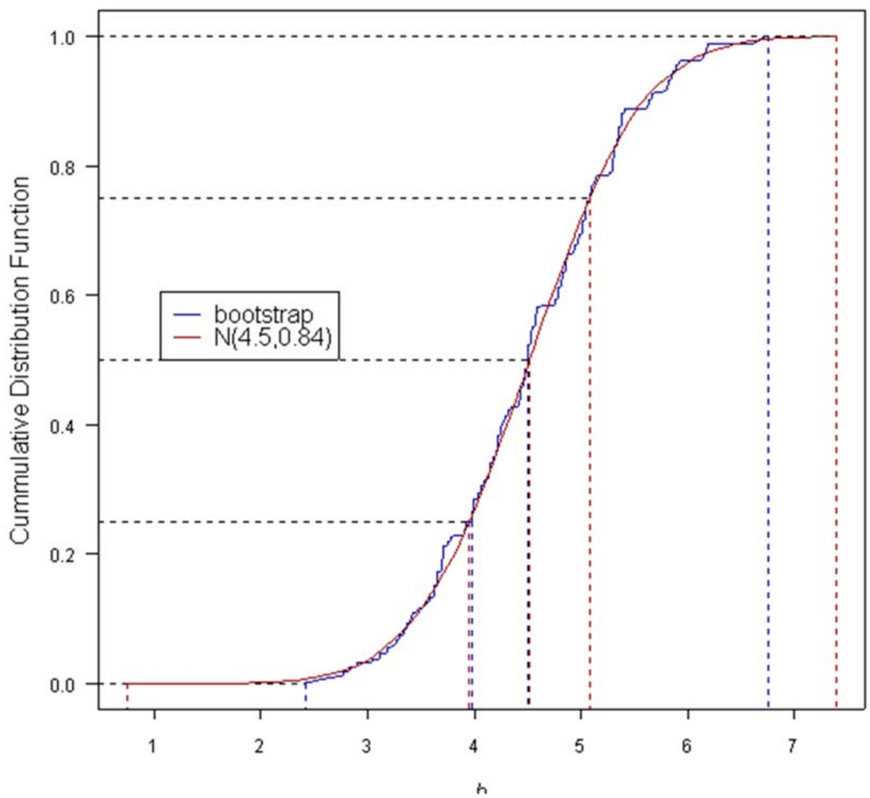


Figure 3. Comparison of bootstrap and normal distributions for the average of the small mammals burrow volume with depth parameter *b* (from Neptune, 2006).

4.6 Burrow Density as a Function of Depth

The *b* parameter describes the burrow density as a function of depth, and alters the form and volume of the excavated burrow, completely analogous to its definition for the shape of plant roots, described in Section 3.5. As the value of *b* increases, the fraction of burrow excavated at each depth moves from being evenly distributed to a highly skewed distribution with most of the excavation occurring near the soil surface. Since no below-ground measurements were obtained on mammal burrows at WCS, this version of the WCS Site Model uses the *b* parameter derived

by Neptune (2006) for rodents at the Nevada National Security Site (NNSS, formerly the Nevada Test Site) (Figure 3). The *b* parameter, defined based on analysis of NNSS data, resulted in a parameter estimate of 4.5 and a standard deviation of 0.84, truncated at 1 and Large.

5.0 Ant Specifications and Parameters

5.1 Ant Conceptual Model

Ants fill a broad ecological niche in arid ecosystems as predators, scavengers, trophobionts and granivores. However, it is their role as burrowers that is of interest for the purposes of the WCS Site Model. Ants burrow for a variety of reasons but mostly for the procurement of shelter, the rearing of young and the storage of foodstuffs. How and where ant nests are constructed plays a role in quantifying the amount and rate of subsurface soil transport to the ground surface at the WCS site. Factors relating to the physical construction of the nests, including the size, shape, and depth of the nest, are key to quantifying excavation volumes. Factors limiting the abundance and distribution of ant nests, such as the abundance and distribution of plant species, and intra-specific or inter-specific competitors, also can affect excavated soil volumes. Parameters related to ant burrowing activities include nest area, nest depth, rate of new nest additions, excavation volume, excavation rates, colony density, and colony lifespan. These attributes are described in this section, along with other considerations involving the influences of ant activities and their incorporation into the WCS Site Model.

The calculations of contaminant transport due to ant burrowing involve three steps:

1. Identify which of the ant species potentially contribute to the rearrangement of soils near the surface at WCS.
2. Calculate soil and contaminant excavated volume using maximum depth, nest area, nest volume, colony density, colony life span, and turnover rate for predominant ant species.
3. Calculate burrow density as a function of depth to determine the distribution of contaminants within the vertical soil profile for each predominant ant species.

Modeling soil and contaminant transport by ant species within the WCS Site Model considers that ants move materials from lower cells to the ground surface while excavating chambers and tunnels within a nest. These chambers and tunnels collapse over time and return soil from upper cells back to lower cells. Through this process the balance of materials is preserved. Soil and contaminant movement from one cell to another is calculated as follows. Within each layer, the fraction of excavated ant nest volume and the fraction of contaminants contained within that layer are determined. The fraction of contaminants within the excavated volume is based on the ratio of the excavated volume to total volume of each layer and is modeled as being distributed homogeneously within the layer. Secondly, the sum of contaminants from each layer associated with ant nest is calculated such that all excavations from layers below are deposited in the uppermost layer. Finally, downward movement of contaminants associated with chamber and tunnel collapse from each layer to the layer below is calculated and the net movement of contaminants into each layer is determined. The amount of contaminants in each layer is then used to adjust contaminant inventory in each layer for the next time step. Thus, the modeled

contaminant transport processes due to ant activity are analogous to those due to the activities of fossorial mammals.

5.2 Identification of Ant Species Important to Bioturbation at WCS

Ant species were selected based on review of "Texas Ants" on AntWeb v4.125, online at http://www.antweb.org/texas.jsp. This resource lists 280 ant species as occurring in Texas, though only a fraction of those are likely to be important in the movement of significant volumes of soil. For purposes of the WCS Site Model, emphasis is placed on the harvester ant genus *Pogonomyrmex* due to their large, long-lived colonies that have been shown to be important to soil bioturbation in arid environments (Hooten et al., 2004). Representative harvester ants from the genera *Pogonomyrmex* were selected based on reported nesting and habitat preferences, as well as the availability of species-specific information to parameterize the model. In particular, the rough harvester ant, *P. rugosus*, and the western harvester ant, *P. occidentalis* were utilized due to their widespread occurrence in the Southwestern U.S. and their habits of forming large, long-lived colonies that can often occur in high densities when seeds of preferred food plants are abundant.

5.3 Ant Nest Volume

A total of 19 *P. rugosus* nests were excavated by Neptune and Company researchers at NNSS (Neptune, 2006), and the information from those excavations is used here for the nest volume distribution. During the excavation activities, galleries and chambers were followed down through the nest to their lowest depths by carefully following the trunk routes of the ants. When the lowest chamber was reached, excavations were made approximately 50 to 100 cm deeper than the chamber to confirm the bottom of the chamber as the maximum depth. Based on these excavations, nest volume and the underground dimensions of the nests were recorded. As reported in Neptune (2006), a bootstrapped distribution for nest volume was produced using the data from the excavation of the 19 nests collected during field trips in 2004 to the NNSS.

The cumulative distributions for both the bootstrapped data and a normal distribution were compared (Figure 4) and the normal distribution was deemed a reasonable fit to the data. Thus, a normal distribution centered at 0.64 m^3 with a standard deviation of 0.091 m^3 was used to model *P. rugosus* nest volume.

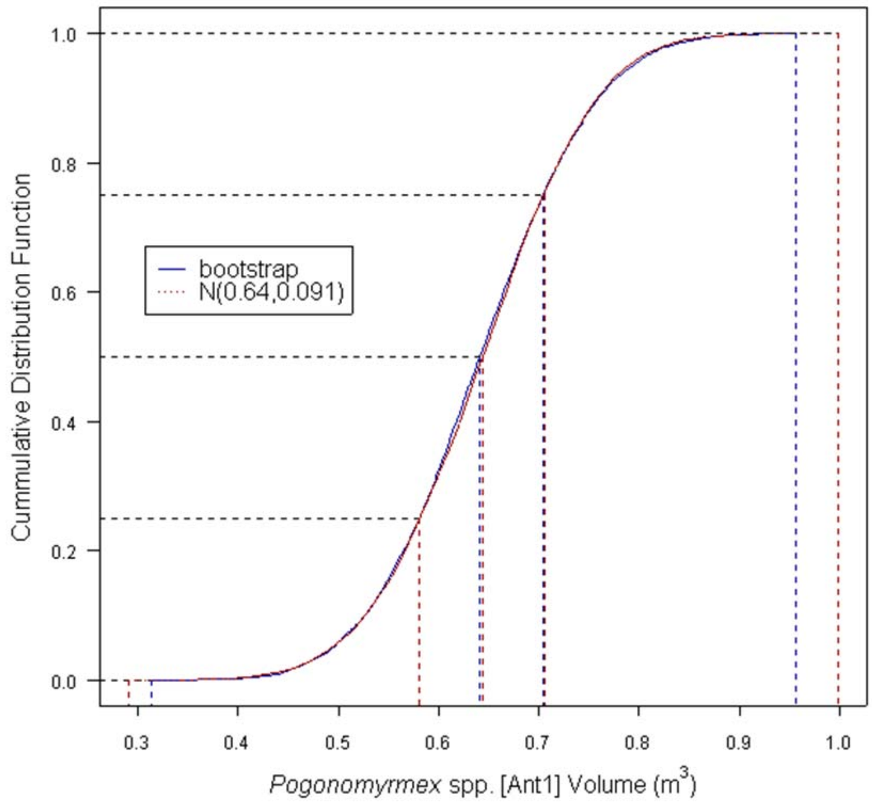


Figure 4. Bootstrapped and normal distributions for *Pogonomyrmex spp*. nest volume from Neptune (2006).

5.4 Maximum Nest Depth

A maximum nest depth was determined by review of literature-reported nest depths for representative ant species present in West Texas. The literature review focused principally on *P. rugosus* and *P. occidentalis* due to their expected occurrence at WCS. A summary of the reported nest depths for these species is presented in Table 8. The WCS Site Model uses ant nest depth as a scalar value, so a nest depth distribution was not used. The maximum reported nest depth of 4.0 m is used as the scalar value to represent ant nest depth.

Table 8. Review of ant nest depths for *Pogonomyrmex rugosus* and *P. occidentalis*

Species	Ant Nest Depth (m)	Citation	Notes
Pogonomyrmex rugosus (rough harvester ant)	1.25 to *4.0*	McKay, 1981	20 excavations of *P. rugosus* from Appendix 1 of reference
	2.44	Neptune, 2006	From p. 21 of reference
Pogonomyrmex occidentalis (western harvester ant)	1.27 to 2.26	Lavigne, 1969	Range based on 20 nest excavations
	3.0 (Kansas) 2.4 (South Dakota)	Fitzner et al., 1979	*P. occidentalis* depths from Table 8 of reference.
Pogonomyrmex occidentalis (western harvester ant)	1.4 to 2.0	Rogers and Lavigne, 1974	P. 995 of reference

5.5 Colony Lifespan

An important component in modeling excavation volume is the turnover rate, or the fraction of the volume of the ant nest that is excavated in any given year. The turnover rate itself is inversely related to the life span of the colony. Table 9 shows four literature studies that report colony lifespan for *P. occidentalis* or *Pogonomyrmex spp*. These *Pogonomyrmex spp*. entries are included because the *P. occidentalis* study simply suggests colony lifespan is greater than 7 years, indicating that the study did not continue until colony failure. The non-specific studies include one entry that suggests a range of 15 to 20 yrs, one that suggests a range for the queen of 17 to 30 but only 2 to 17 for the nest, and an entry of 20.2 ± 8.1 (standard deviation) based on 5 observations. The NNSS cover modeling (Neptune, 2006) used the latter entry, including the information that there were 5 data points. Since the standard deviation was based on 5 observations, the standard deviation of 8.1 was divided by the square of 5 to arrive at a normal distribution with a mean of 20.2 years and standard deviation of 3.6 years. This same distribution was used here. To ensure non-negative values as well as allow division by colony life, the distribution is truncated at an arbitrarily small value defined in the model.

Table 9. Information for ant colony lifespan

Genera and species	Max nest (n) or queen (q) longevity (yr)	Number of observations	Source
Pogonomyrmex	17–30 (q)		Hölldobler and Wilson 1990
	2–17 (n)		Hölldobler and Wilson 1990
	20.2 ± 8.1	5	Porter and Jorgensen 1988
P. occidentalis (Cresson)	>7 (n)		Hölldobler and Wilson 1990

5.6 Burrow Density as a Function of Depth

Excavation volume gives an overall estimate of how much soil is being transported to the soil surface, but it is also important to determine the density of burrowing activities as a function of depth within the vertical soil profile. The shape of the nest under the surface expression of the nest gives insight into the quantity of contaminated soils at various depths being excavated to the surface. The burrow density as a function of depth is described by the fitting parameter *b*, completely analogous to the fitting parameter of the same name used for mammal burrows and plant roots. The fitting parameter developed in the NNSS study (Neptune, 2006) for all *Pogonomyrmex* species is used in the model. Based on bootstrapping (similar to that performed for ant nest volume above), a normal distribution with a mean of 10 and standard deviation of 0.71, truncated at 1, was estimated for *b* for *Pogonomyrmex* nests at NNSS (Neptune, 2006).

5.7 Colony Density

Colony densities were estimated from literature for *Pogonomyrmex* species that could potentially occur at WCS.

Due to a lack of available information needed to characterize the geometry of nests for *P. barbatus* and *P. desertorum*, the distributions that will be developed to inform the ant nest area density parameter are informed using data only from *P. rugosus* and *P. occidentalis*.

As for the mammal burrow area densities, as well as most other parameters in the model, the ant colony area densities represent a spatio-temporal average. That is, a value that is constant both across space and through time. Of course, there is still uncertainty associated in the value representing the ant nest area density.

For the WCS site, the statistically uninformed prior is used and updated using data from both *P. rugosus*, and *P. occidentalis*. Using the same distribution development procedure outlined for the mammal burrow area density, the distribution used to inform the WCS Site Model is gamma(mean = 14.36, standard deviation = 1.094).

Table 10. Summary of reported nest densities for *Pogonomyrmex* species potentially occurring at the WCS site

Species	Ant Nest Area Density (1/ha)	Citation	Notes
Pogonomyrmex rugosus (Rough harvester ant)	21	McKay, 1981	From Table 3 of reference
	6.3 – 20.5	McKay, 1981	From Table 3 of reference
	1 - 25	McKay, 1981	From Table 3 of reference
	1 - 47	Neptune, 2006	Section 6.6 of reference
Pogonomyrmex barbatus (Texas harvester ant)	20.3 – 34.7	Gordon and Kulig, 1996	

Pogonomyrmex desertorum (desert harvester ant)	115	McKay, 1981	From Table 3 of reference
Pogonomyrmex occidentalis (western harvester ant)	3 - 31	McKay, 1981	From Table 3 of reference
	2 - 33	SWCA, 2011	From Table 20 of reference

6.0 References

Andersen, D.C., and D. W. Johns. 1977. *Predation by Badger on Yellow-Bellied Marmot in Colorado*. The Southwestern Naturalist, 22(2): 283-284.

Bienek, G.K., and A.W. Grundmann. 1971. *Burrowing Habits of Two Subspecies of Dipodomys merriami in California and Utah*. Great Basin Naturalist, 31(3): 190-192.

Borjigidai A, K. Hikosaka, and T. Hirose. 2009. *Carbon balance in a monospecific stand of an annual herb Chenopodium album at an elevated CO_2 concentration*. Plant Ecology 203: 33-44.

California Department of Fish and Game. 1999. *Merriam's Kangaroo Rat. California's Wildlife*. Sacramento, CA. http://www.sibr.com/mammals/M110.html

Carter, D.C., Webster, W.D., Jones, J.K., Jones, C., and R.D. Suttkus. 1985. *Dipodomys elator. Mammalian Species*, No 232. American Society of Mammalogists.

Davis, William B., and David J. Schmidly, 1997, The Mammals of Texas, Online Edition. http://www.nsrl.ttu.edu/tmot1/Default.htm.

Desha, P.G. 1966. *Observations on the Burrow Utilization of the Thirteen-lined Ground Squirrel*. The Southwestern Naturalist, 11: 408-410.

Dhillion, S.S. 1999. *Environmental heterogeneity, animal disturbances, microsite characteristics, and seedling establishment in a Quercus havardii community*. Restoration Ecology 7(4):399-406.

Edwards, R.L. 1946. *Some Notes on the Life History of the Mexican Ground Squirrel in Texas*. J. Mammal. 27: 105-116.

Engel, R.K., J.T. Nichols, J.L. Dodd, and J.E. Brummer. 1998. *Root and shoot responses of sand bluestem to defoliation*. Journal of Range Management 51(1)42-46.

Fitzner, R.E., K.A. Gano, W.H. Rickard, and L.E. Rogers. 1979. *Characterization of the Hanford 300 Area Burial Grounds: Task IV – Biological Transport*. PNL-2774, UC-70. Pacific Northwest Laboratory, Richland, WA.

Gordon, D.M. and A.W. Kulig. 1996. *Founding, Foraging, and Fighting: Colony Size and the Spatial Distribution of Harvester Ant Nests*. Ecology, 77(8): 2393-2409.

Grant, D.W., D.P.C. Peters, G.K. Beck, and H.D. Fraleigh. 2003. *Influence of an exotic species, Acroptilon repens (L.) DC. on seedling emergence and growth of native grasses*. Plant Ecology 166: 157-166.

Hibbard, K.A., A. Archer, D.S. Schimel, and D.W. Valentine. 2001. *Biogeochemical changes accompanying woody plant encroachment in a subtropical savanna*. Ecology 82(7): 1999-2011.

Hölldobler, B., and E.O. Wilson. 1990. *The Ants*. The Belknap Press of Harvard University Press, Cambridge, Massachusetts. 732 pp.

Hoogland, J.L., Angell, D.K., Daley, J.G., and M.C. Radcliffe. 1987. *Demography and Population Dynamics of Prairie Dogs*. Great Plains Wildlife Damage Control Proceedings. Paper 72.

Hooten, M.M. et al. 2004. *A Literature Review of Biotic Components, Processes, and Characteristics Central to Biotic Transport Modeling of Soils at the Nevada Test Site*. Neptune and Company, Inc., Los Alamos, NM

Idaho State University. 2000. *Taxidea taxus* (American Badger). Online at:http://imnh.isu.edu/digitalatlas/bio/mammal/Carn/muste/amba/badger.htm Accessed March 4, 2013.

Kurc, S.A., and E.E. Small. 2004. *Dynamics of evapotranspiration in semiarid grassland and shrubland ecosystems during summer monsoon season, central New Mexico*. Water Resources Research, 40: W09305.

Lavigne, R.J. 1969. *Bionomics and Nest Structure of Pogonomyrmex occidentalis (Hymenoptera: Formicidae)*. Ann. Ent. Soc. Am. 62(5): 1166-1175.

Laundré, J.W., and T.D. Reynolds. 1993. *Effects of Soil Structure on Burrow Characteristics of Five Small Mammal Species*. Great Basin Naturalist, 53(4): 358-366.

Long, K. 2002. *Prairie Dogs, A Wildlife Handbook*. Johnson Publishing Company, Boulder CO.

Maganti M., S. Weaver, and M. Downs. 2005. *Responses of spreading orach (Atriplex patula) and common lambsquarter (Chenopodium album) to soil compaction, drought, and waterlogging*. Weed Science 53(1): 90-96.

Marcum, K.B., M.C. Engleke, and S.J. Morton. 1995. *Rooting Characteristics of Buffalograsses Grown in Flexible Plastic Tubes*. HortScience 30(7): 1390-1392.

McKay, W.P. 1981. *A Comparison of the Nest Phenologies of Three Species of Pogonomyrmex Harvester Ants (Hymenoptera: Formicidae)*. Psyche, 88: 25-74.

Mirik M. and R.J. Ansley. 2012. *Utility of satellite and aerial images for quantification of canopy cover and infilling rates of the invasive woody species honey mesquite (Prosopis glandulosa) on rangeland*. Remote Sensing 4: 1947-1962.

Moore G.W., D.A. Barre, and M.K. Owens. 2010. *Changes in soil chloride following shrub removal and subsequent regrowth*. Geoderma 158: 148-155.

Neptune and Company, 2006, *Ant Parameter Specifications for the Area 5 and Area 3 RWMS Models*. Prepared for DOE Nevada by Neptune and Company, Inc., Los Alamos, NM

NRC (U.S. Nuclear Regulatory Commission), 1992, *Residual Radioactive Contamination from Decommissioning – Technical Basis for Translating Contamination Levels to Annual Total Effective Dose Equivalent: Final Report*, NUREG/CR-5512 V1, Prepared for the U.S. Nuclear Regulatory Commission by W.E. Kennedy and D.L. Strenge, Pacific Northwest Laboratory, Richland, WA.

Perkins S.R., and M.K. Owens. 2003. *Growth and biomass allocation of shrub seedlings in response to predicted changes in precipitation seasonality*. Plant Ecology 168: 107-120.

Peters D.P.C., 2002. *Plant species dominance at a grassland-shrubland ecotone: an individual-based gap dynamics model of herbaceous woody species*. Ecological Modeling 152: 5-32.

Porter, S.D., and C.D. Jorgensen. 1988. *Longevity of Harvester Ant Colonies in Southern Idaho*. Journal of Range Management 46(2): 104-107.

Qian Y.L., J.D. Fry, and W.S. Upham, 1997. *Rooting and drought avoidance of warm-season turfgrasses and tall fescue in Kansas*. Crop Science 37(3) 905-910.

Reagan and Associates, 2004. *Habitat Characterization and Rare Species Survey for the Proposed Low Level Waste Repository, Andrews County, Texas*, Attachment 1A in Appendix 2.9.1 *Ecological Assessment* of the License Application (WCS, 2007).

Rogers, L.E. and R.J. Lavigne. 1974. *Environmental Effects of Western harvester Ant on the Shortgrass Plains Ecosystem*. Environ. Entomol., 3(6): 994-997.

Sheets, R.G., R.L. Linder and R.B. Dahlgren. 1971. *Burrow systems of prairie dogs in South Dakota*. J. Mammal. 52: 451-453.

Steinberg, Peter. 2001. *Prosopis glandulosa*. In: Fire Effects Information System, [Online]. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fire Sciences Laboratory (Producer). Available: http://www.fs.fed.us/database/feis/ [2013, February 15]. Full URL: http://www.fs.fed.us/database/feis/plants/tree/progla/all.html

Streubel, D.P., and J.P. Fitzgerald. 1978. *Spermophilus spilosoma. Mammalian Species*, No 101. American Society of Mammalogists.

Sullivan, J. 1995. *Dipodomys ordii. In: Fire Effects Information System*, [Online]. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fire Sciences Laboratory (Producer). Available: http://www.fs.fed.us/database/feis/ [2013, February 26].

SWCA. 2001. *Field Sampling of Biotic Turbation of Soils at the Clive Site, Tooele County, Utah*. Prepared for Energy*Solutions*. January 2011.

Travlos, I.S., 2013. *Responses of invasive silverleaf nightshade (Solanum elaeagnifolium) populations to varying soil water availability*. Phytoparasitics 41: 41-48.

Van Vuren, D.H., and M.A. Ordeñana. 2012. *Burrow Dimensions of Ground Squirrels, with Special Reference to the California Ground Squirrel*. California Levee Vegetation Research.

WCS, 2007, *Application for License to Authorize Near-Surface Land Disposal of Low-Level Radioactive Waste, Revision 12c*, Waste Control Specialists, Dallas, TX, 1 May 2007.

White, J.A. 2009. *Summer Burrows of Ord's Kangaroo Rats (Dipodomys ordii) in Western Nebraska: Food Content and Structure*. Western North American Naturalist, 69(4): 469-474.