Coupled Environmental Processes in the Mojave Desert and Implications for ET Covers as Stable Landforms

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Abstract

Monolayer evapotranspiration (ET) covers are the baseline method for closure of disposal sites for low-level radioactive waste (LLW), mixed LLW, and transuranic (TRU) waste at the Nevada Test Site (NTS). The regulatory timeline is typically 1,000 years for LLW and 10,000 years for TRU waste. Covers for such waste have different technical considerations than those with shorter timelines because they are subject to environmental change for longer periods of time, and because the environmental processes are often coupled. To evaluate these changes, four analog sites (approximately 30, 1,000 to 2,000, 7,000 to 12,500, and 125,000 years in age) on the NTS were analyzed to address the early post-institutional control period (the youngest site), the 1,000-year compliance period for disposal of LLW, and the 10,000-year period for TRU waste. Tests included soil texture, structure, and morphology; surface soil infiltration and hydraulic conductivity; vegetation and faunal surveys; and literature reviews. Separate measurements were made in plant undercanopy and intercanopy areas. The results showed a progressive increase in silt and clay content of surface soils with age. Changes in soil texture and structure led to a fivefold decline in saturated hydraulic conductivity in intercanopy areas, but no change in undercanopies, which were subject to bioturbation. These changes may have been responsible for the reduction in total plant cover, most dramatically in intercanopy areas, primarily because more precipitation either runs off the site or is held nearer to the surface where plant roots are less common. The results suggest that covers may evolve over longer timeframes to stable landforms that minimize the need for active maintenance.

Introduction

Vegetated, evapotranspiration or "ET" covers are rapidly gaining acceptance at arid and semi-arid sites for waste site closure based on water-balance and related studies being conducted at sites such as those at Sandia National Laboratories, New Mexico (Dwyer, 2003), and the Hanford Nuclear Reservation, Washington (Gee *et al*., 1997). In addition, at more than a dozen sites across the United States (U.S.) through the U.S. Environmental Protection Agency's Alternative Cover Assessment Program (http://www.dri.edu/Projects/EPA/boston-brochure2.html), ET components have been incorporated into alternative cover designs. Other facilities, such as the Edwards Air Force Base in California, are developing site-wide closure strategies for disposal sites using ET covers (Young *et al*., 2004a). Evapotranspiration covers are a significant departure from traditional closure cover designs. Rather than attempting to restrict infiltration of water, the ET cover allows water to infiltrate into the cover material where natural processes of evapotranspiration and evaporation remove it. At the Nevada Test Site (NTS), monolayer ET covers have been selected as the baseline technology for closure of landfills being used for low-level radioactive waste (LLW), mixed LLW, as well as areas of shallow-land disposal of transuranic (TRU) and mixed TRU waste (Bechtel Nevada, 2001).

However, vegetated ET covers cannot be viewed as static features, but rather as features subject to natural processes of change, the same as any alluvial/colluvial landform, particularly after cover maintenance ends. These changes, and their subsequent effect on long-term cover performance, are difficult to capture in performance modeling because, in many cases, they are poorly understood. Among the most significant shortcomings is our understanding of the relationships between soil water dynamics, soil morphologic development, and plant ecology in arid regions (McDonald, 2002). Thus, the goals of this study were to identify a landform chronosequence at the NTS, describe the sites for soil morphologic, hydrologic, and biotic characteristics, and then analyze the characteristics for interrelationships that would indicate the coupling of environmental processes.

Materials And Methods

Site Description

The NTS, managed by the U.S. Department of Energy (DOE), is located 105 kilometers northwest of Las Vegas, Nevada (Figure 1). Yucca Flat, where the analog sites are located, is a structurally closed basin in the northeast quadrant of the NTS, encompassing an area of about 780 km^2. The Yucca Flat Playa, normally dry, is situated on the southern end of the basin. Average annual precipitation is about 16 cm based on a 1960 to 2003 summary of data (http://www.sord.nv.doe.gov/home_climate_MEDA.htm). On average, 57 percent of annual precipitation on the NTS occurs between November and March.

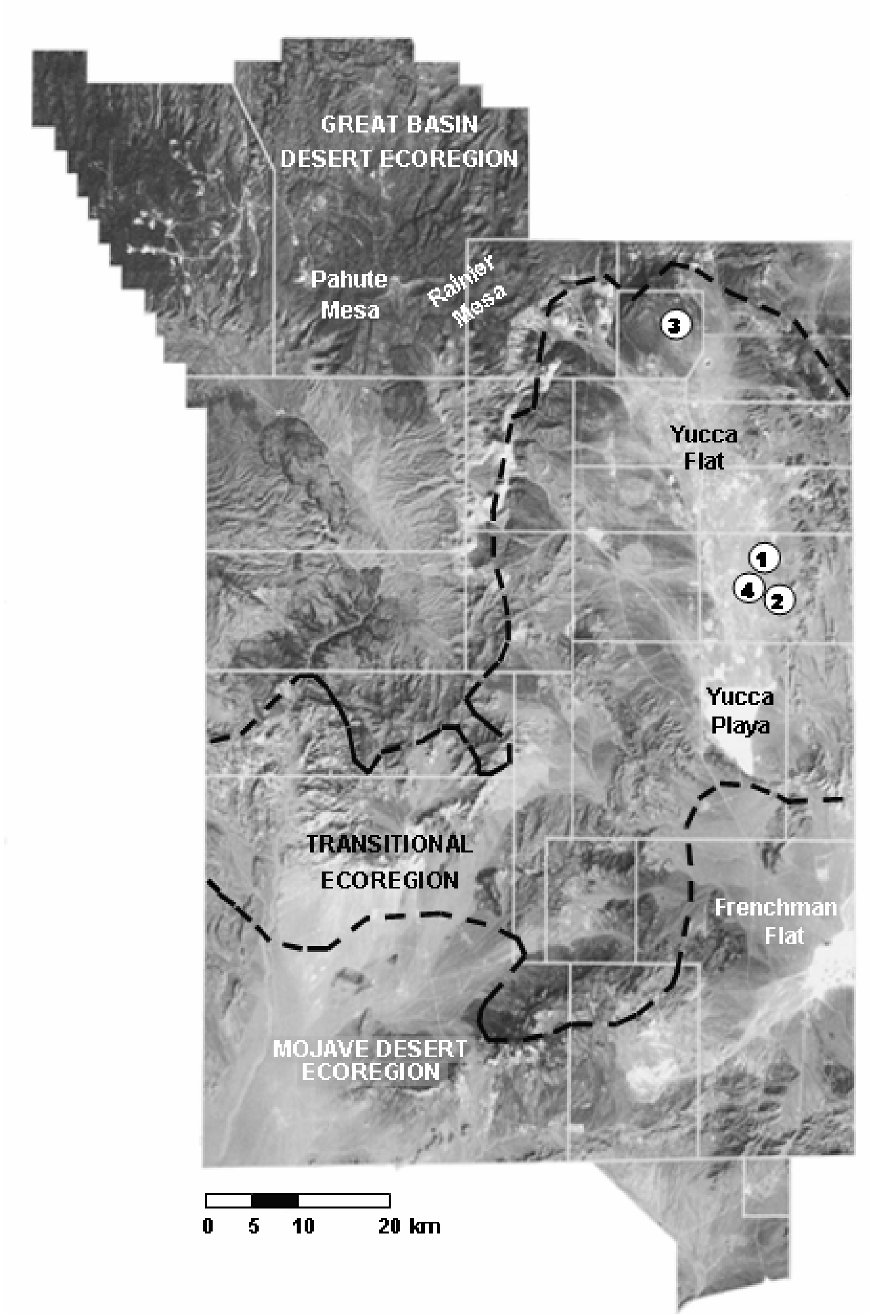

Figure 1. **The Nevada Test Site, located 105 km northwest of Las Vegas, Nevada. Analog Sites 1, 2, and 4 are on the east side of Yucca Flat, while Site 3 is on the north end of the basin. The analog sites are in a transition zone between the Mojave and Great Basin desert ecoregions (Wills and Ostler, 2001).**

Analysis of Analog Sites

Site Selection

The analog sites (Site 1: ~30 years; Site 2: 1,000 to 2,000 years; Site 3: 7,000 to 12,500 years; and Site 4: ~125,000 years in age) were selected to addresses changes in the early post-institutional control period (the youngest site), the 1,000-year compliance period for disposal of LLW and mixed LLW, and the 10,000-year compliance period for TRU waste sites. Analog sites were selected based on criteria that included 1) evidence that the sites had been isolated from recent alluvial, colluvial, and erosional processes that would not be expected to be agents on newly constructed ET covers; 2) low surface gradients, eliminating the need to consider processes such as sheet wash that a newly constructed cover would also be designed not to experience; 3) minimal anthropomorphic impacts, or, if present, their impacts were clearly distinguished from natural processes; and 4) that some means of obtaining age control could be established for the site (Shafer *et al.*, 2004). The four sites are located within an elevation range of 1,261 and 1,483 m in Yucca Flat, which lies within an ecosystem transition region between the Mojave Desert and the Great Basin (Wills and Ostler, 2001).

Biotic Surveys

At each site, a series of 5 x 10 m subplots were established in a 50-m-long belt transect in which all perennial plants had their rectangular coordinates and their canopy heights and widths measured (Zitzer *et al.*, 2004). Plant nomenclature was based on Hickman (1993). Winter annual plant diversities and density were measured in five paired subplots at each site. Annuals were noted as living in the undercanopy of perennial shrubs or, when at least 0.5 m from the shrub canopy edge, as being in the intercanopy area. The frequency and size of animal burrows were also measured and their distribution noted as being in undercanopy or intercanopy environments. The depth of animal burrows was noted in soil trenches constructed at Sites 1, 2, and 3. A literature review was conducted to determine possible burrowing vertebrate and invertebrate species at the sites, and their habits that would affect the depth and distribution of their burrows.

Soil Morphology

Soils were described from trenches constructed at Sites 1, 2, and 3. Trenches were dug to a depth at which the maximum fine rooting depth was observed. Representative bulk samples for laboratory analysis were collected from each horizon from paired undercanopy and intercanopy soil profiles. Soil characteristics were described in accordance with U.S. Natural Resources Conservation Service soil survey methods (USDA, 1999) as well as those of Birkeland (1999). Soils were analyzed for particle-size distribution using laser light scattering (Gee and Or, 2002), carbonate content using Chittick apparatus (Dreimanis, 1962; Machette, 1985), and electrical conductivity (Rhoades, 1996). Using methods from Birkeland (1999), particle-size distribution of the less than 2 mm fraction is shown as percent weight of each major fraction (sand, silt, clay) and weight percent of each subfraction (Table 1). Abbreviations used in soil morphology descriptions are from USDA (1999).

Table 1. Average ± standard deviation for textural components of material sampled at intercanopy and undercanopy areas. Gravel fraction is the weight percent of the entire sample >2 mm. The remaining textural analysis involves only the fine-earth fraction (<2 mm).

Intercanopy

Year	%Gravel[1]	%Sand[2]	%Silt[3]	%Clay[4]
30	49.3 ± 5.2	79.7 ± 6.0	14.5 ± 1.9	5.8 ± 2.5
1,000 to 2,000	35.8 ± 7.8	80.2 ± 3.0	14.2 ± 0.5	5.7 ± 2.4
7,000 to 12,500	55.6 ± 17.7	55.6 ± 6.0	28.3 ± 2.6	16.1 ± 1.9
125,000	31.6 ± 21.0	50.6 ± 3.9	34.1 ± 1.7	15.3 ± 3.8

Undercanopy

Year	%Gravel[1]	%Sand[2]	%Silt[3]	%Clay[4]
30	38.6 ± 7.8	84.1 ± 3.0	10.9 ± 1.1	5.0 ± 1.2
1,000 to 2,000	33.0 ± 13.4	80.7 ± 2.8	15.6 ± 1.1	3.7 ± 0.8
7,000 to 12,500	26.4 ± 7.9	65.1 ± 5.0	23.0 ± 1.6	11.9 ± 5.4
125,000	27.2 ± 12.6	70.4 ± 8.0	23.0 ± 2.8	6.6 ± 2.6

[1]%Gravel is representative of the total sample > 2 mm.
[2]%Sand of the fine-earth fraction ranging from 62.5 μm to 2,000 μm.
[3]%Silt of the fine-earth fraction ranging from 3 μm to 62.5 μm.
[4]%Clay of the fine-earth fraction < 2 μm.

Hydraulic Property Estimation

The tension infiltrometer (TI) method (Ankeny *et al.,* 1988; Reynolds and Elrick, 1991) was used for determining the soil hydraulic properties of the surface soil. Paired locations of undercanopy and intercanopy locations were identified in undisturbed areas adjacent to the biotic transects. Five paired locations were identified at each site, with the locations for the canopy area chosen to maximize the spacing between measurements. The locations for the intercanopy were chosen to be within one to two meters of the shrub used for canopy measurements. Triplicate measurements were taken whenever possible to account for spatial variability of hydraulic properties.

Measurements followed the procedures described by Casey and Derby (2002) and Young *et al.* (2004b), using four to five tension steps for each test, typically at levels -12, -9, -6, -3, and 0 (saturation) cm. At the conclusion of each test, a bulk density sample of the soil was collected for volumetric water content and particle-size distribution analysis. In total, 48 TI tests were conducted at the four sites, with at least three measurements for any particular treatment used to calculate the mean. Two analytical methods were used for solving for hydraulic conductivity (K_{sat}) (see Table 2). The semi-empirical, nonlinear least-squares regression routine for Wooding's Analysis was used to solve for two unknowns ($Ksat_w$ and α_w) by minimizing error through iterative solutions (Logsdon and Jaynes, 1993). A numerical inversion method using the HYDRUS-2D model (Simunek *et al.,* 1996) provided a complete set of hydraulic properties. The hydraulic properties refer to the soil water retention curve (van Genuchten, 1980), and the hydraulic conductivity equation derived by Mualem (1976) and modified by van Genuchten (1980). Results produced a series of fitting parameters and physical properties of the soil that were cross-correlated to geomorphic and age setting and the hydraulic properties. Correlation tables were constructed to identify the most sensitive parameters affecting hydraulic properties.

Table 2. Results of field analyses of hydraulic properties at the four analog sites. K_{sat} and alpha parameters are represented as geometric mean. Other parameters are arithmetic mean.

Wooding's Analysis – Intercanopy

~ Age (years)	$Ksat_w$ (cm/d)	α_w (cm^{-1})	R^2
30	119.12	0.268	0.951
1,000 to 2,000	87.95	0.133	0.948
7,000 to 12,500	66.56	0.181	0.930
125,000	25.27	0.123	0.961

Wooding's Analysis – Undercanopy

~ Age (years)	$Ksat_w$ (cm/d)	α_w (cm^{-1})	R^2
30	75.01	0.313	0.961
1,000 to 2,000	147.18	0.260	0.940
7,000 to 12,500	55.13	0.180	0.887
125,000	81.01	0.251	0.950

HYDRUS-2D Analysis - Intercanopy

~ Age (years)	θs	α_{vg} (cm^{-1})	n	$Ksat_{vg}$ (cm/d)	1/α (cm)	R^2
30	0.262	0.137	1.495	280.02	7.29	0.997
1,000 to 2,000	0.269	0.060	2.522	86.98	16.58	0.999
7,000 to 12,500	0.304	0.086	1.753	109.10	11.59	0.999
125,000	0.215	0.064	2.454	27.95	15.56	0.998

HYDRUS-2D Analysis – Undercanopy

~ Age (years)	θs	α_{vg} (cm^{-1})	n	$Ksat_{vg}$ (cm/d)	1/α (cm)	R^2
30	0.318	0.204	1.378	392.74	4.90	0.997
1,000 to 2,000	0.397	0.182	1.471	131.16	5.50	0.997
7,000 to 12,500	0.316	0.127	1.586	275.88	7.87	0.998
125,000	0.341	0.102	1.713	398.77	9.82	0.999

Results And Discussion

Using the field methods described above, it was clear that the most significant soil-forming process observed at the sites was the development of an Av vesicular soil horizon, commonly found in desert soils in the southwest U.S. and formed from the long-term accumulation of aeolian silt and clay below the soil surface (McFadden *et al.*, 1998). Intercanopy development of Av horizons began at Site 2 (1,000 to 2,000 years old) with the development of Avj1 and Avj2 horizons. At Site 3, a well-developed and thick (10 cm) Av horizon developed (Figure 2a). The percent silt/clay is actually higher at Site 3 than Site 4, likely because it is situated at the north end of Yucca Flat, which contributes significant aeolian material. In contrast, soils in the undercanopy areas at all the sites exhibited abundant signs of faunal and floral bioturbation. The AC soil horizons at Sites 2 and 3 are largely composed of soil material excavated from below by animals. The excavated material forms circular and conical mounds that extend slightly beyond the edge of the shrub canopy (Figure 2b). While an overall increase with time of aeolian-deposited material was observed, Av and Avj horizons were discontinuous and mixed due to bioturbation and have morphological properties similar to BC and BCk horizons.

(a)

(b)

Figure 2. A well-developed Av horizon at 10 to 20 cm depth in a soil trench at the 7,000-12,500-year-old site (a), and conical mounds of lighter-toned soil formed by bioturbation in the undercanopy of shrubs at the 1,000- to 2,000-year-old sites (b).

Development of the near-surface, platy-structure Av horizon was found to restrict water infiltration into the soils profile, and thus water percolation to deeper horizons where plants roots are located. Coupled with the development of desert pavement at Site 3 by 10,000 yr BP, the pedogenic development of the Av horizon probably accounts for a significant decrease in K_{sat} in intercanopy areas over time. The decrease is most evident using the parameter estimation method, in which a fivefold decrease in K_{sat} in intercanopy areas over time was observed. Results of Wooding's Analysis also showed a decrease with increasing site age, although less consistently than with HYDRUS-2D (Figure 3). In contrast to the intercanopy areas, K_{sat} remains relatively constant in the undercanopy areas based on both Wooding's and parameter estimation analyses. We hypothesize that bioturbation in the undercanopy areas from small mammals as well as perennial plant rooting probably prevented the development of Av horizons, which was found (Young et al., 2004a) at other sites in the Mojave Desert to control water entry into soil.

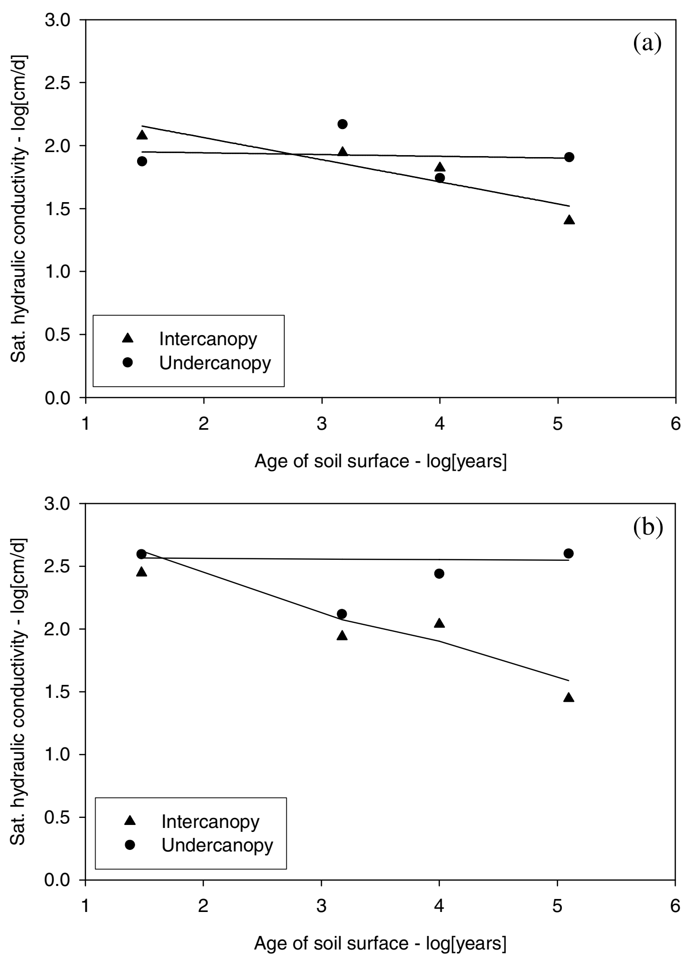

Figure 3. Geometric means of K_{sat} using the semi-empirical (a) Wooding's Analysis, and parameter estimation (b) based on HYDRUS-2D methods, for intercanopies and undercanopies. Regression models are shown as solid lines.

As site age increased, percent perennial plant cover increased to a maximum of 31 percent on Site 3 (7,000 to 12,500 years old), although it decrease to 23 percent at Site 4 (125,000 years old). For all sites, shrubs made up greater than 85 percent of total cover. However, a strong disconnect was observed between peaks in species richness and plant density versus percent cover (Figure 4). Total annual plant density peaked at 246 plants/m^2 at Site 1 (1,000 to 2,000 years old), declined by 55 percent on Site 3, and continued to decline by 83 percent at Site 3. In addition, the highest annual plant density occurred at Site 2 (1,000 to 2,000 years old), and may reflect the period of time when water balance was most affected by transpiration. With increasing age, the development of soil structure such as the Av horizon in the intercanopy areas and the resultant decrease in K_{sat} produced significant contrasts in vegetation density in the intercanopy and undercanopy environments. For example, when comparing annual plant densities at Sites 2 and 3, the undercanopy remained greater than 200 plants/m^2, while intercanopy density decreased by 73 percent. Thus, it appears that pedologic development, especially the surface features of the soil structure and Av horizons, could be reducing the amount of infiltration and/or increasing the water holding capacity of the surface soils, in both cases reducing the depth of wetting front penetration and hence the amount of plant-available water.

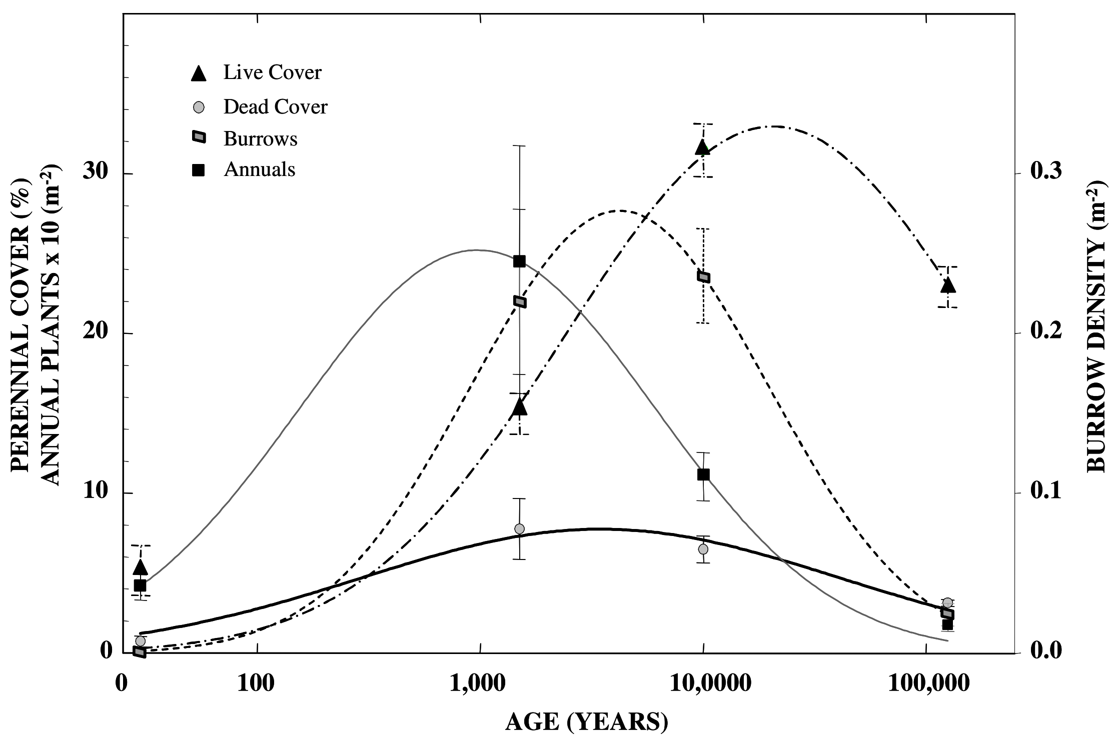

Figure 4. Age relationships between plant cover and winter annual and burrow densities at the four analog sites. Data are plotted at the midpoint of the age range for each site.

Conclusions

Results suggests the presence of complex interactions over time between pedogenic development, hydrology, and biotic activity, but that ET covers allowed to develop naturally may lead toward stable landforms that minimize the need for active maintenance. At any one time, both evapotranspiration and transpiration processes probably contribute to the success of ET covers. However, if the respective roles of "E" and "T" are partitioned over time, soil morphologic development dramatically increases the roles of transpiration over time in maintaining water balance for LLW and TRU covers.

While the study of analog sites suggests that ET covers can evolve naturally for effective performance, cover designs need to incorporate "ingredients" necessary for favorable natural processes to occur. Furthermore, some common cover "maintenance" activities may actually set back natural processes that promote the development of stable cover landforms. For example, the study sites suggest that bioturbation may actually initiate the process of desert pavement development. Surface disturbance outside of shrub canopies from small mammal activity, particularly early in the development of covers, may lead to higher vegetation cover from perennial shrubs and annuals during the period of time when transpiration plays a greater role in water balance for ET covers. While subsurface biological activity could be viewed as a threat to long-term cover performance, the maximum depth of active burrows and krotovina (older, filled-in burrows) coincided with the depth of larger roots, and decreased from a maximum of 0.70 m at Site 1 to 0.30 m at Site 3. Further, consideration of the burrowing characteristics of animals could be used to construct *de facto* barriers. For example, the only rodent species in the study region capable of excavating soil particles of 5 cm or larger is the Botta's pocket gopher (*Thomomys bottae*) (Winkel *et al*., 1995). Mixed clast size in the biologically active zone of a cover could inhibit the development of macropores from burrows or krotovina.

A legitimate concern is whether the development of the Av horizon and desert pavement, and concomitant decrease in K_{sat}, could result in higher surface runoff that could damage the structural integrity of a cover. However, the lowest K_{sat} estimated was 25 to 81 cm/day, depending on the analytical approach, values still high enough to allow water entry from most storms that would affect the region.

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