MONITORING THE PERFORMANCE OF AN ALTERNATIVE COVER USING CAISSON LYSIMETERS

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ABSTRACT

The U.S. Department of Energy (DOE) office in Grand Junction, Colorado, and the U.S. Environmental Protection Agency (EPA), Region 8, collaborated on a series of field lysimeter studies to design and monitor the performance of an alternative cover for a uranium mill tailings disposal cell at the Monticello, Utah, Superfund Site. Because groundwater recharge is naturally limited at Monticello in areas with thick loess soils, DOE and EPA chose to design a cover for Monticello using local soils and a native plant community to mimic this natural soil-water balance.

Two large drainage lysimeters fabricated of corrugated steel culvert lined with high-density polyethylene were installed to evaluate the hydrological and ecological performance of an alternative cover design constructed in 2000 on the disposal cell. Unlike conventional, low-permeability designs, this cover relies on (1) the water storage capacity of a 163-cm soil "sponge" layer overlying a sand-and-gravel capillary barrier to retain precipitation while plants are dormant and (2) native vegetation to remove precipitation during the growing season. The sponge layer consists of a clay loam subsoil compacted to 1.65 g/cm^2 in one lysimeter and a loam topsoil compacted to 1.45 g/cm^2 in the other lysimeter, representing the range of as-built conditions constructed in the nearby disposal cell cover.

About 0.1 mm of drainage occurred in both lysimeters during an average precipitation year and before they were planted, an amount well below the EPA target of <3.0 mm/yr. However, the cover with less compacted loam topsoil sponge had a 40% greater water storage capacity than the cover with overly compacted clay loam subsoil sponge. The difference is attributable in part to higher green leaf area and water extraction by plants in the loam topsoil. The lesson learned is that seemingly subtle differences in soil types, sources, and compaction can result in salient differences in performance. Diverse, seeded communities of predominantly native perennial species were established on both lysimeters during an extended 3-yr drought, highlighting the importance of a sound understanding of the local ecology and of implementing the science and methods of disturbed-land revegetation.

INTRODUCTION

The Monticello, Utah, mill, built in 1942 to provide vanadium for World War II, later processed nearly 1.0 million tons of uranium ore and produced more than 2.5 million m^3 of tailings before its closure in the early 1960s. The U.S. Department of Energy (DOE) office in Grand Junction, Colorado, Region 8 of the U.S. Environmental Protection Agency (EPA), and the State of Utah Department of Environmental Quality collaborated on the design and construction of a disposal cell to contain tailings and tailings-contaminated materials at Monticello. Remedial actions were regulated under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA). The disposal cell design satisfied both (1) minimum technology guidance for hazardous waste disposal facilities [1] under subtitle C of the

Resource Conservation and Recovery Act of 1976 (RCRA) and (2) design guidance for radon attenuation and 1,000-yr longevity [2] under the Uranium Mill Tailings Radiation Control Act of 1978 (UMTRCA).

Early cover designs constructed for UMTRCA disposal cells typically consist of compacted soil layers (CSLs), sand drains, and rock riprap intended to function as physical barriers to radon releases, water infiltration, and erosion.[2, 3] Typical RCRA cover designs also include prescribed physical barriers.[1] These conventional engineered covers, which attempt to resist natural processes rather than work with them, will likely require increasing maintenance.[4] After only a few years, CSLs have desiccated and cracked under routine wetting and drying conditions [5], and biological disturbances threaten cover integrity at many sites.[6, 7, 8, 9, 10] The goal at Monticello was to design an engineered cover system that enhances beneficial natural processes to help make long-term containment possible.[11]

At semiarid sites such as Monticello, relatively low precipitation (P), high potential evapotranspiration (PET), and thick unsaturated soils seem to favor long-term hydrologic isolation of buried waste.[12, 13, 14, 15] But simple P/PET relationships inadequately predict recharge in arid regions that can approach 60% of precipitation in coarse-textured soils denuded of vegetation.[16] At arid and semiarid waste disposal sites, recharge can be minimized with thick, fine-textured soil layers that store precipitation in the root zone where evapotranspiration (ET) seasonally removes it.[17, 18, 19, 20, 21] Capillary barriers consisting of coarse-textured sand and gravel placed below this soil "sponge" layer can enhance water storage and limit unsaturated flow.[22, 23] To be accepted by regulators, end users must demonstrate that the water balance of these alternative cover designs is at least equivalent to conventional designs.

Weighing and drainage lysimeters offer the most direct and reliable means for evaluating soil-water balance of alternative cover designs.[24] Lysimeters have been used for many years to evaluate irrigation needs [25] and have been used more recently to test the hydrologic performance of waste landfill cover designs.[26, 27, 28, 29] DOE and EPA conducted a series of field lysimeter experiments at Monticello beginning in 1990 to help design and then monitor the performance of a disposal cell cover that would rely in part on a high soil water-storage capacity and high ET to limit infiltration and leaching of contaminants from tailings.[30]

This paper presents the status of a lysimeter study of an alternative cover design at Monticello, Utah. The purposes of this study are (1) monitor the hydrological and ecological performance of the Monticello design for as-built conditions in the actual cover and (2) evaluate the general application of the design as an alternative to EPA design guidance for arid and semiarid sites.

STUDY AREA: CLIMATE, SOILS, AND VEGETATION

The study area is adjacent to the tailings disposal cell 2 km south of Monticello, Utah. Monticello is semiarid with cold, windy winters and mild summers. The 30-yr average (1961–1990) annual precipitation is 39 cm. The average minimum January temperature is -10.5 °C and the average July maximum temperature is 28.9 °C. The year can be characterized as three seasons with respect to soil-water balance: November through March, the season of deep infiltration and moisture accumulation in soils (average precipitation equals 16 cm); April through June, a moisture-depletion period when plants become water stressed (average precipitation equals 6 cm); and July through October, a season of variable shallow moisture accumulation and depletion resulting from monsoonal convection storms (average precipitation equals 17 cm). Annual snowfall averages 160 to 170 cm.

The soils within the footprint of the Monticello disposal cell formed in Pleistocene loess.[31] The taxonomic classification is Monticello very fine sandy loam.[32] The soil texture varies from clay loam to sandy loam. The natural vegetation of the Monticello very fine sandy loam at the disposal cell site consists primarily of Western wheatgrass (Pascopyrum smithii [Rydb.] Á. Löve), Sandberg bluegrass

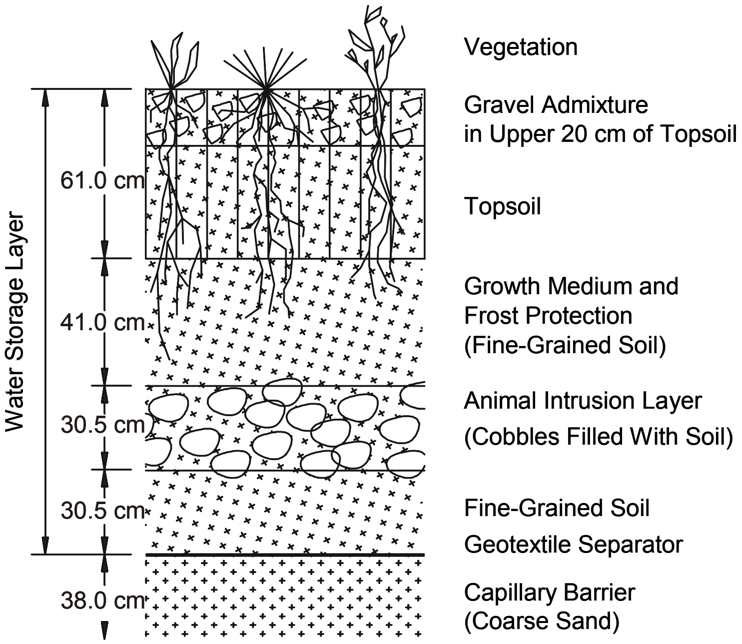
(Poa secunda J. Presl), blue grama (Bouteloua gracilis [Kunth] Lag.), mountain big sagebrush (Artemisia tridentata Nutt. subsp. vaseyana [Rydb.] Beetle), and rubber rabbitbrush (Ericameria nauseosa [Pallas ex Pursh] Nesum & Baird) with a canopy coverage of 50% to 60%.[32]

COVER DESIGN AND LYSIMETER INSTALLATION

Installation of a cover on the Monticello disposal cell similar to the RCRA Subtitle C design [1] began in fall 1998. The disposal cell has a double liner and a leachate collection system with a design permeability of 1 x 10^{-9} cm/s. EPA accepted a design with a geomembrane and a CSL in the cover to ensure that water flux through the cover will not exceed flux through the liner—at least in the short term. Because of the uncertain durability of the geomembrane and the CSL, the design incorporates an alternative cover system as the primary means for limiting percolation for the long term.

Alternative Cover Design

The Monticello alternative cover design (Figure 1) is fundamentally an ET cover with a capillary barrier.[33] The design relies on the water-storage capacity of a 163-cm fine-textured soil layer (sponge) overlying a 38-cm sand capillary barrier layer to retain precipitation until it is seasonally removed by vegetation (solar pumps). Leakage into the sand should occur only if water accumulation at the sponge/sand layer interface approaches saturation and tensions decrease sufficiently for water to enter the larger pores of the sand layer. Hydraulic performance can be evaluated as the probability that, over time, ET is sufficient to prevent water accumulation in the soil sponge from exceeding the storage capacity.[11]



Fig, 1. Alternative cover design tested in caisson lysimeters and constructed on a uranium mill tailings disposal cell at the Monticello Superfund Site.

Other components of the Monticello design either facilitated construction or were included to enhance long-term performance. A geotextile fabric maintains the fine-grained soil/coarse sand layer discontinuity during construction and until soil aggregation occurs by natural pedogenic processes.[34] The combination of vegetation and gravel admixture controls erosion. Vegetation and organic litter disperse raindrop energy, shield underlying fine soils, increase infiltration, reduce water flow and surface wind velocity, bind soil particles, and filter sediment from runoff.[35] Gravel mixed into the surface helps control erosion when vegetation is sparse (following construction, fires, drought, etc.), mimicking conditions that lead to the formation of gravel pavements. The gravel admixture can control both wind and water erosion [36, 37] and, functioning as a mulch, can enhance seedling emergence and plant growth.[20]

The Monticello design includes frost protection, deterrents for biointrusion, and other attributes for plant growth. The depth is more than adequate to isolate the underlying RCRA components (CSL and geomembrane) from frost damage.[38] The soil sponge thickness is also the primary biointrusion deterrent. Water retention in the soil sponge creates habitat for relatively shallow-rooted plants, and the thickness of the sponge exceeds the depth of most burrowing vertebrates in the Monticello area. A layer of cobble-size rock 30.5 cm above the capillary barrier is an added deterrent should deeper burrowers, such as prairie dogs, move into the area in response to climate change. Fine-textured sponge soil fills the interstices of the rock layer, preventing it from behaving like a second capillary barrier. The topsoil layer, obtained from the root zone of the borrow area, has physical and hydraulic properties similar to the rest of the soil sponge, but also contains available nutrients, propagules, and microorganisms (e.g., mycorrhizae) needed for the establishment of a sustainable plant community.

Lysimeter Installation and Soil Materials

We installed two large drainage lysimeters to evaluate the range of as-built conditions in the actual Monticello alternative cover. Lysimeter 1 closely matches the materials and compaction as built during the latter stages of construction. Lysimeter 2 mimics less desirable materials and compaction as built during the early stages of construction.

Pleistocene eolian soils from the lysimeter excavation were used for the fine-grained sponge layers in Lysimeter 1. The upper 61 cm was stockpiled topsoil that had been separated from subsoils. Lysimeter 1 sponge soil layers were compacted to about 1.45 g/cm^3, closely matching the dry-weight bulk density of native Monticello very fine sandy loam. Fine-grained sponge soils for Lysimeter 2, taken from the disposal cell stockpile, consisted of a mixture of loess soils and underlying pediment paleosols, the material used during early stages of the cover construction. Lysimeter 2 sponge layers were compacted to about 1.65 g/cm^3, closely matching the bulk density achieved during the early stages of construction.

A combination of sieve and hydrometer methods [39] was used for soil particle-size analysis (Table I). The U.S. Department of Agriculture (USDA) soil textural classes for Lysimeters 1 and 2 sponge soils are loam and clay loam, respectively. Because sample volumes were inadequate for accurate analysis of gravel splits, representative sampling and analysis of all materials will be conducted at the conclusion of the study.

Table I Soil Particle Size[a] and Dry-Weight Bulk Density[b] for Lysimeters 1 and 2.

Layer	Class[c]	CG (%)	FG (%)	VCS (%)	CS (%)	MS (%)	FS (%)	VFS (%)	Si (%)	Cl (%)	B.D.[b] (g/cm^3)
Lysimeter 1											
Gravel Admixture	GL	13	2	–	–	1	7	23	31	23	–
Fine-Grain Topsoil	L	–	–	–	1	1	5	24	45	24	–
Fine-Grain Soil A	L	3	2	2	2	2	7	23	36	27	1.44
Biointrusion Barrier[c]	GL	38	11	2	3	4	6	9	15	12	–
Fine-Grain Soil B	L	3	9	5	5	3	7	15	29	24	1.45
Capillary Barrier	S	–	37	9	15	21	12	3	2	1	–
Compacted Soi	L	4	1	1	1	2	7	18	39	27	1.75
Lysimeter 2											
Gravel Admixture	GClL	13	2	3	4	4	6	15	29	24	–
Fine-Grain Soil A[e]	ClL	–	1	1	1	1	8	30	28	30	1.64
Biointrusion Barrier[c]	GL	49	16	2	1	2	3	5	13	9	–
Fine-Grain Soil B[e]	ClL	–	10	3	4	5	6	15	31	26	1.66
Capillary Barrier	S	–	38	13	9	12	20	3	3	2	–

[a] USDA soil particle-size classes: CG = coarse gravel (10–70 mm); FG = fine gravel (2–10 mm); VCS = very coarse sand (1–2 mm); CS = coarse sand (0.5–1 mm); MS = medium sand (0.25–0.5 mm); FS = fine sand (0.1–0.25 mm); VFS = very fine sand (0.05–0.1 mm); Si = silt (0.002–0.05 mm); Cl = clay (<0.002 mm).

[b] Dry-weight bulk density (B.D.) was determined using a nuclear gauge. Sample size $n \geq 3$.

[c] USDA soil texture classes: L = loam, GL = gravely loam, ClL = clay loam, GClL = gravely clay loam, S = sand. Only fine-grained splits (VCS and finer) were used for soil textural classification.

[d] Gravel percentages in the biointrusion layer are inaccurate because of inadequate sample volumes.

[e] Gravel percentages in the fine-grain layers in Lysimeter 2 will be determined at the conclusion of the study.

Construction of the first of two caisson lysimeters (Lysimeter 1) began in fall 1998. We excavated a pit approximately 8 m in diameter by 3 m in depth, using a track hoe, at an existing lysimeter test facility [30] adjacent to the Monticello tailings disposal cell. Eolian and pediment soils excavated from the pit were segregated in stockpiles. A corrugated steel culvert, 3.05 m in diameter by 2.75 m in depth, forms the walls of Lysimeter 1. Access to instrumentation is through an adjacent caisson, 1.52 m in diameter by 3.66 m in depth. We bolted the steel culverts (lysimeter caisson and instrument access caisson) together, lowered them into the pit using a track hoe bucket, and aligned them vertically. We installed Lysimeter 2 adjacent to Lysimeter 1 in fall 1999 (Figure 2). Lysimeter 2 is 2.44 m deep. Caissons were partially backfilled to create a compacted floor with a 20:1 slope and a drainage port at the low end.

The caisson lysimeters were lined with 40-mil high-density polyethylene (HDPE), filled with water, covered with plastic, and leak tested using a manometer. HDPE tubes, welded to drainage holes cut into the lower end of the HDPE floor liner, were inserted through ports into the access caisson. We constructed cover layers in lysimeters by marking soil lift heights on the interior walls, hauling and dumping stockpiled materials into the lysimeters, spreading and wetting lift materials, and then tamping lifts to achieve soil bulk-density specifications. Bulk density was measured with a nuclear density gauge (Troxler Inc.). Instrumentation was installed as the cover layers were constructed. Twenty-cm wide HDPE flaps were heat-welded to the HDPE walls, at a depth of about 60 cm below the lips of the lysimeters, to divert any preferential flow of water along the sidewall back into the soil mass.

Plant Establishment

Revegetation goals for ET covers include plant communities that (1) are well-adapted to the engineered soil habitat, (2) are capable of high transpiration rates, (3) limit soil erosion, and (4) are structurally and functionally resilient.[40] Seeding of monocultures or low-diversity mixtures on engineered covers is common. Instead, revegetation should attempt to emulate the structure, function, diversity, and dynamics of native plant communities in the area. Diverse mixtures of native and naturalized plants will maximize water removal and remain more resilient given variable and unpredictable changes in the environment resulting from pathogen and pest outbreaks, disturbances (overgrazing, fire, etc.), and climatic fluctuations. Local indigenous ecotypes that have been selected over thousands of years are usually best adapted. In contrast, the exotic grass plantings common on engineered covers are genetically and structurally rigid, are more vulnerable to disturbance or eradication by single factors, and will require continual maintenance. Successful establishment of a diverse and resilient plant community requires the enlistment of practitioners knowledgeable in the science and methods of disturbed land revegetation.

Revegetation of the lysimeters matched the specifications and methods used for the adjacent tailings disposal cell.[41] We seeded the lysimeters in September 2000 with a mixture of grasses, forbs, and shrubs in an attempt to mimic the potential natural vegetation for the borrow soils and local climate (Table II). Seed was hand-broadcasted, raked, and tamped into the soil surface, and the surface was mulched with straw. Several species were also transplanted. Plants selected for the lysimeters are perennial, native, cool-season species except as indicated in Table II.

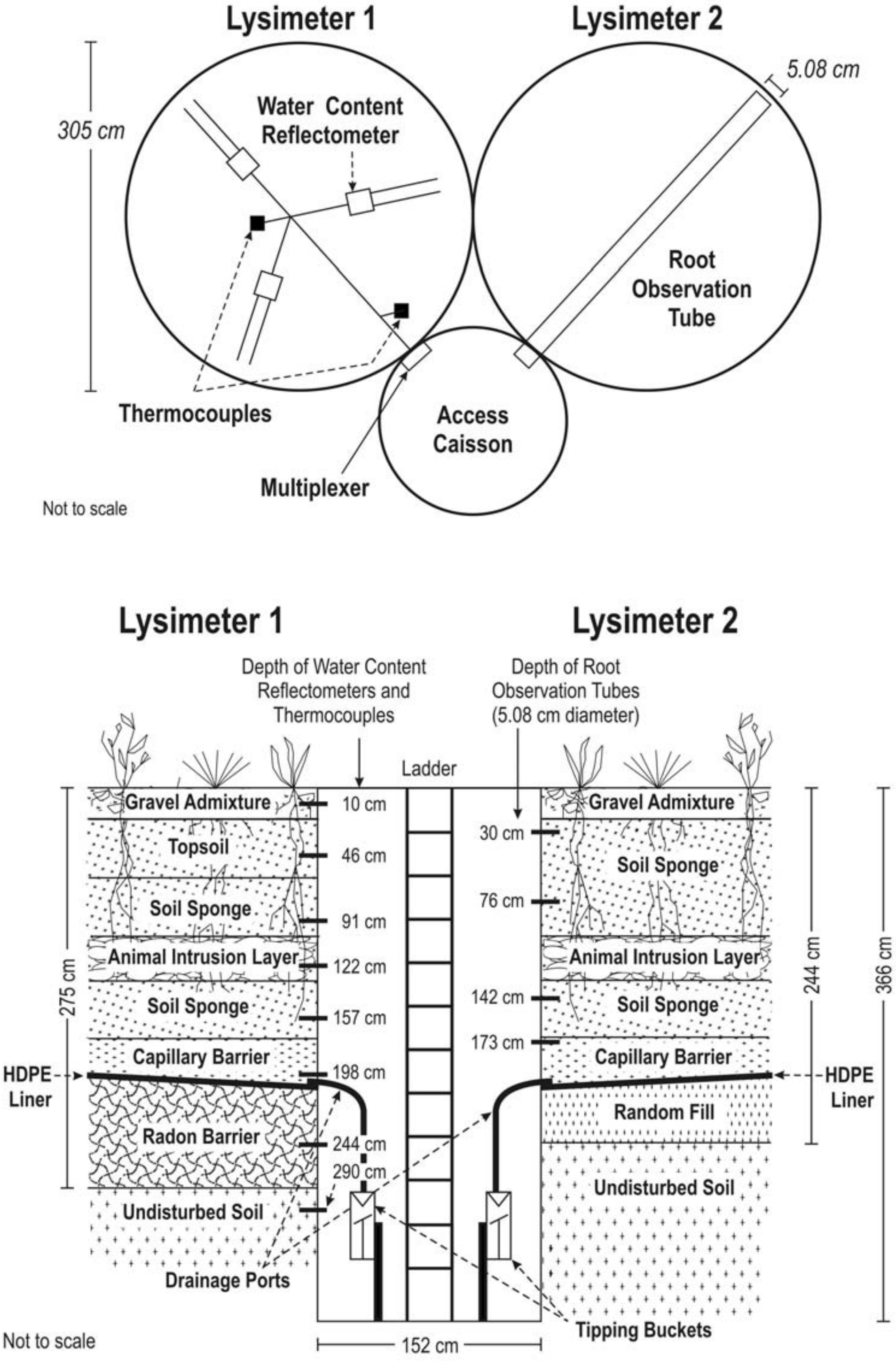


Fig. 2 Plan view (top) and cross section (bottom) of instrumentation in the lysimeter and access caissons. Water Content Reflectometers, thermocouples, and root observations tubes, shown separately for purposes of illustrating layouts and depths, were all installed in both lysimeters.

PERFORMANCE MONITORING METHODS AND RESULTS

Evaluating the performance of alternative covers depends on careful analysis of climate, soil hydrology, and plant ecology. Lysimeters enable us to evaluate performance of the cover as a system—an integrated whole—over diurnal, seasonal, and yearly time scales. Our monitoring instrumentation and methods focused on the components of the soil-water balance (precipitation, changes in water storage, drainage, and evapotranspiration) and on plant community composition and relative abundance. Monitoring began during the 1999 growing season for Lysimeter 1 and a year later for Lysimeter 2. This section presents the meteorological, soil-water balance, and vegetation monitoring methods and results as of October 2003.

Table II Species Planted on the Lysimeters.

Scientific Name	Common Name	PLS/Acre[a]
Shrubs		
Ericameria nauseosa	Rubber rabbitbrush	1.5
Purshia tridentata	Antelope bitterbrush	1.0
Artemisia tridentate var. tridentata	Mountain big sagebrush[b]	0.5
Artemisia tridentata var vaseyana	Basin big sagebrush	0.1
Artemisia tridentate var. wyomingensis	Wyoming big sagebrush	0.05
Forbs		
Linum lewisii	Blue flax[b]	2.0
Astragalus cicer	Cicer milkvetch[c]	1.6
Sphaeralcea coccinea	Scarlet globemallow[d]	0.5
Sphaeralcea grossulariifolia	Gooseberry globemallow[d]	0.5
Erigeron speciosus	Aspen daisy	0.15
Achillea millefolium var. lanulosa	Common yarrow	0.12
Aster tanacetifolius	Prairie aster[e]	0.05
Grasses		
Bromus carinatus	Mountain brome[b]	4.0
Elymus lanceolatus	Thickspike wheatgrass	3.0
Pascapyrum smithii	Western wheatgrass[b]	3.0
Stipa comata	Needle and thread grass	2.0
Stipa hymenoides	Indian ricegrass	2.0
Bouteloua gracilis	Blue grama[d]	1.0
Hilaria jamesii	Galleta grass[d]	1.0

[a] PLS/acre = pure live seed per acre.
[b] Plants seeded and transplanted onto small lysimeters.
[c] Annual or biennial.
[d] Warm season (C^4) species.
[e] Not native.

Soil-Water Balance

The primary objective of the caisson lysimeter study is to evaluate the soil-water balance of the as-built cover. The overall soil-water balance of a cover would include inputs of precipitation (P) and run-on (Ri) and outputs of evapotranspiration (ET), drainage past plant roots in the soil profile (D), and runoff (Ro). Soil-water storage changes (ΔS) can be expressed as

$$\Delta S = P + Ri - ET - D - Ro. \tag{Eq. 1}$$

The caisson lysimeter soil surfaces are isolated from Ri and Ro, thus ET can be estimated using a simplified water balance equation

$$ET = P - D - \Delta S, \tag{Eq. 2}$$

where ET, P, and ΔS are recorded as linear units (mm or cm) of water.

Direct measurement of all water-balance terms was not possible. For the Monticello study, precipitation, drainage, and water storage changes are monitored, and actual ET is estimated by difference. Potential ET can be estimated by calculation of the energy budget (Penman-Montieth equation) using the field parameters of wind speed, relative humidity, solar radiation, and air temperature.

Meteorological Conditions A weather station was installed to monitor meteorological conditions in July 2000. The meteorological station consists of a 3-m-high tripod anchored in concrete with supports for sensors and enclosures. The weather station was configured to provide data for the following parameters:

Parameter	Sensor
Wind speed	Cup anemometer
Wind direction	Vanes that use precision potentiometer
Solar radiation	Thermopile pyranometer
Air temperature	Platinum resistance temperature detector
Relative humidity	Capacity sensors that use integral signal conditioning
Precipitation	Tipping-bucket rain gauge

The weather station uses a programmable data logger (CR23X, Campbell Scientific, Inc., Logan, Utah) that records sensor measurements and stores data. Sensory measurements are stored hourly and daily. Conditional outputs, such as rainfall intensity, are also processed and stored. The data logger is wired to alternating current and data are downloaded via phone modem.

Total annual precipitation has been less than the 30-yr average (39 cm) since the lysimeters were planted in 2000 (Table III). The 2002 growing season was particularly dry, with winter and spring precipitation about 50% and 15% of normal, respectively. Precipitation was only 57% of normal between November 2000 and June 2002, the critical period for plant establishment.

Table III Annual and Seasonal Precipitation (cm) at Monticello.

Year[a]	Annual	November–March[b]	April–June[b]	July–October[b]
Average	39.0	16.0	6.0	17.0
2000				17.4
2001	25.7	10.6	5.7	9.4
2002	22.9	8.0	0.9	14.0
2003		21.0	11.0	

[a] Annual precipitation calculated for November through October of the current year.

[b] Yearly precipitation characterized as three seasons with respect to soil-water balance: November through March is the season of deep infiltration and moisture accumulation in soils; April through June is a moisture-depletion period when plants become water

stressed; and July through October is a season of variable shallow moisture accumulation and depletion resulting from monsoonal convection storms.

Soil-Water Storage and Drainage Measurements

Soil moisture and water storage are monitored with CS-615 water content reflectometers (WCRs) manufactured by Campbell Scientific, Inc. (Logan, Utah). WCRs consist of two, 30-cm-long parallel rods attached to an electronic signal generator. A pulsed wavelength traveling down a coax, or waveguide, is influenced by the type of material surrounding the conductors. If the dielectric constant of the material is high, the signal propagates slower. Because the dielectric constant of water is much higher than most other materials, a signal within a wet medium propagates slower than in the same medium when dry. The reflectometer measures the effective dielectric as a pulse transit time, which in turn is calibrated against water content. Changes in soil moisture are determined by reading the WCR probes hourly.

In each lysimeter, 18 WCRs monitor water content within the cover layers with three replicate measurements at six depths:

Depth (cm)	Material
10	Gravel admixture layer
45	Topsoil layer of soil sponge
90	Fine-grain soil sponge layer
120	Animal intrusion barrier layer
160	Soil sponge layer just above capillary interface
200	Capillary barrier layer, near the bottom

Additional WCRs monitor water content in Lysimeter 1 with three replicate measurements at a depth of 240 cm in the compacted soil layer (radon barrier) and three replicate measurements at a depth of 290 cm in native soil below the engineered cover.

Because probe-to-probe variability is insignificant [42], we calibrated WCRs after the lysimeters were filled. WCR calibrations were determined for all soil materials using 30-cm-diameter by 80-cm-deep polyvinyl chloride (PVC) calibration cells. Soil materials were compacted in 10-cm lifts to match the dry-weight bulk density attained in the lysimeters. Calibrations for each material were obtained for soil moisture contents ranging between air dry and saturation, from approximately 8% to 40% by volume. Calibrations were repeated for three different WCRs to check probe-to-probe variability. WCRs were inserted vertically near the center of a filled PVC cell until the rods were completely covered with soil, five readings were taken for each soil/moisture combination with the probe embedded in a different location each time, and then five volumetric samples were collected spanning the depth of the WCR rods.

Water-content reflectometers, thermocouples, and root observations tubes were placed in shallow trenches cut into the soil lifts. Root observation tubes consist of 5-cm-diameter by 3-m-long clear Lexan cylinders placed horizontally from sealed ports in the access caisson through the center of the lysimeter caisson. Table IV presents layer materials and depths, WCR and thermocouple placement depths, mean WCR calibration coefficients, and depths of root observation tubes. Drainage, soil water content, and soil temperature data are monitored hourly, stored in the microprocessor on site, and downloaded periodically via phone modem.

Table IV Cover layers, wcr placement depths and calibration, and root tube depths

Layer Material	**Layer Depth (cm)**	**WCR Depth (cm)**	**WCR Calibration Coefficients**			**Root Tube Depth (cm)**
			C0	**C1**	**C2**	
Lysimeter 1						
Gravel Admix	0–20	10	-0.1001	-0.0069	0.1958	
Topsoil	20–61	46	-0.1001	-0.0069	0.1958	30
Sponge Soil	61–102	90	-0.4544	0.6998	-0.1272	76
Biobarrier	102–133	120	-0.2166	0.2362	0.0815	
Sponge Soil	133–163	160	-0.4544	0.6998	-0.1272	147
Sand	163–201	200	0.4161	-1.2964	0.9926	173
Compacted Soil	201–274	240	-0.4544	0.6998	-0.1272	
Native Soil	274+	290	-0.4544	0.6998	-0.1272	
Lysimeter 2						
Gravel Admix	0–20	10	-0.4544	0.6998	-0.1272	
Sponge Soil	20–61	45	-0.4544	0.6998	-0.1272	30
Sponge Soil	61–102	90	-0.4544	0.6998	-0.1272	76
Biobarrier	102–133	120	-0.2166	0.2362	0.0815	
Sponge Soil	133–163	160	-0.4544	0.6998	-0.1272	147
Sand	163–201	200	0.4161	-1.2964	0.9926	173

Soil Water Responses

Time series of drainage and water storage changes show conspicuous seasonal variability and an overall drying trend (Figure 3). Drainage did not exceed 0.1 mm/yr, well below the EPA target of <3.0 mm/yr. The only drainage occurred in spring 2000. The lysimeters were not planted until 2000 to allow water storage to build to the maximum limit for each soil type. No measurable drainage occurred during the dry years while vegetation was maturing.

Time series of soil-water storage are displayed as millimeters of water in Figure 3. In both lysimeters, seasonal high and low water storage occurred in mid-to-late spring and mid-to-late fall, respectively, depending on the amount and seasonality of precipitation, the soil type and

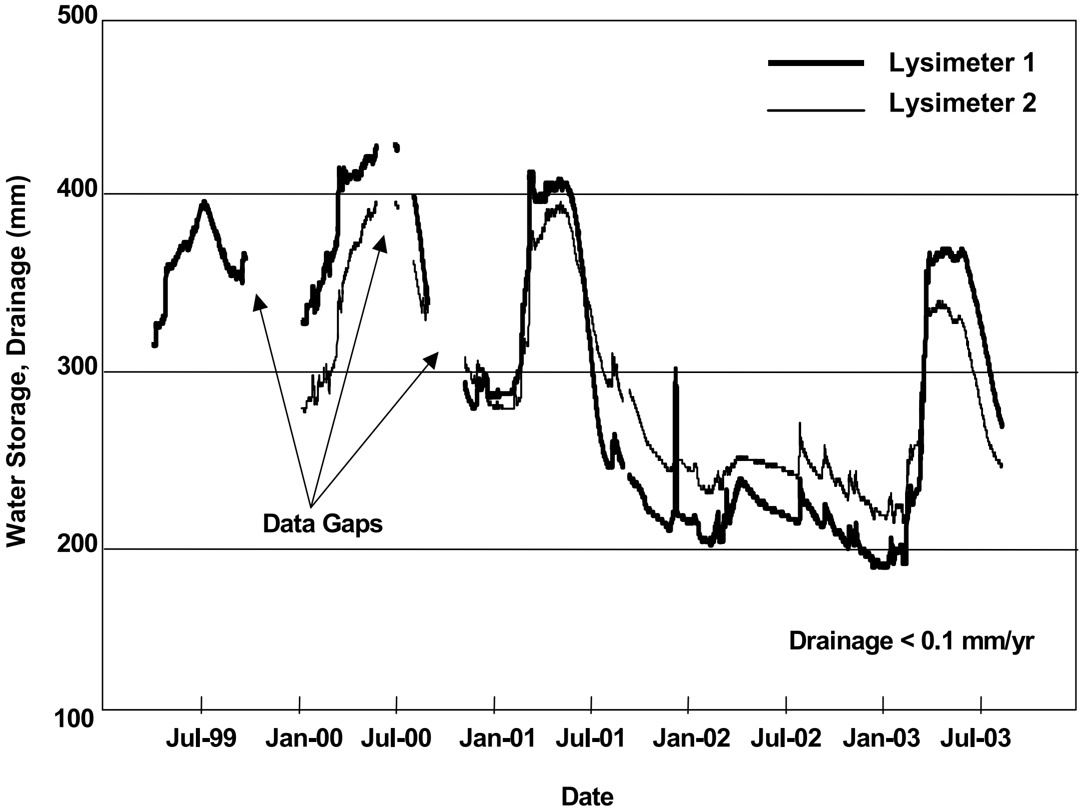


Fig. 3 Soil-water storage time series in Lysimeter 1 (less compacted loam soil sponge) and Lysimeter 2 (more compacted clay loam soil sponge) between July 1999 and August 2003.

compaction, and the maturity of vegetation. The maximum storage in both lysimeters occurred in spring 2000 before plants became established. Because drainage also occurred at that time, water storage may have reached the maximum limit for each soil type: about 440 mm in Lysimeter 1 and 400 mm in Lysimeter 2. The lower maximum storage limit for Lysimeter 2 as compared with Lysimeter 1 may be attributable to a lower porosity in the more compacted clay loam than in the less compacted loam. Once vegetation established during the dry years, the seasonal peak storage did not approach the limit in either lysimeter and no drainage occurred. The peak in spring 2002 was virtually nonexistent because precipitation was virtually nonexistent.

Seasonal low water-storage levels also differed between the two lysimeters. The difference is most likely attributable to plant water extraction (evapotranspiration). During the 2000 growing season, before plants established, the seasonal low remained at about 280 mm; only about a 5-mm difference was observed between lysimeters. After plants became established, water storage in the less compacted loam (Lysimeter 1) dropped below 200 mm, about 30 mm below water storage in the compacted clay loam (Lysimeter 2). The water storage capacity of a soil layer can be calculated as the difference between the maximum storage limit and the lowest measured water storage level after the plant water potential reaches the wilting point. If this definition is used, the water storage capacity for the less compacted loam soil in Lysimeter 1 (about 250 mm) is more than 40% greater than the more compacted clay loam in Lysimeter 2 (about 175 mm). Soil type and layer construction practices can have significant effects on the performance of alternative covers.

Vegetation Composition and Abundance

The water storage data in Figure 3 show that the hydrologic performance of the Monticello cover relies, in part, on the establishment and resilience of a diverse plant community. Plant canopy structure plays a fundamental role in processes involving the interaction of plant communities and their environment, such as ET [43] and biomass productivity.[44] Plant canopy structure can be thought of as the amount and organization of aboveground plant material. Canopy structure may include the size, shape, orientation, and distribution of various plant parts such as leaves, stems, branches, flowers, and fruits. The amount of leaf and stem material in a canopy can be represented by measurements of leaf area index (LAI) and productivity. LAI, the leaf area per unit of ground area, is one of the more useful measures of plant canopy structure because it is also an index of the relative transpiration potential of the canopy. Productivity is the rate of change in biomass per unit time, such as from one year to the next. Percent cover, a more common measure of plant abundance, is the percentage of a unit area (1 m^2, for example) beneath the canopy of a given species.

Methods

Plant species composition and abundance were measured on the caisson lysimeters near the end of the growing seasons in 2002 and in 2003. Species composition and percent cover were measured over the entire 7.3-m^2 lysimeter surface. The lysimeter surface was divided into 50- by 100-cm quadrats delineated with string. A quadrat is an area of ground surface delimited for plant measurement. All plant species in each quadrat were recorded. We used an ocular point-intercept sampling method [45] to measure percent cover in each quadrat.

LAI and productivity of green vegetation (current year's growth) were sampled in half of the quadrats by harvesting green leaf material and running the leaves through a Licor, Inc. LI-3100 Area Meter (www.licor.com). Green leaf material was harvested by hand or cut with shears, placed in paper bags, and processed soon after returning to the laboratory. Artemisia tridentata green leaves were not removed because defoliation can stress or kill the plant. Accuracy of the LI-3100 Area Meter was assessed with a 10-cm^2 calibration disk periodically passed through the meter. Green LAI was computed by dividing the total green leaf area in a quadrat by the quadrat area. Green leaf material was then air dried in paper bags and weighed to estimate productivity. We considered that samples were dry if we measured no change after repeated weighings for several days.

Species Composition, Cover, LAI, and Productivity. Species growing on the lysimeters were grouped based on revegetation acceptance criteria (Table V). Total percent cover for all plants growing in lysimeters, when averaged over years and lysimeters (37.1%, S.E.=0.6%, n = 4), is close to the minimum 40% cover criterion.[41] However, as much as 20.6% cover or 56% relative cover consisted of species either not listed as a permissible species or listed as noxious and non-noxious weeds. Only about 16.5% of the cover consisted of permissible species, well below the requirement. Western wheatgrass (Pascopyrum smithii), the dominant native grass growing on Monticello very fine sandy loam, was also the most abundant species on the lysimeters. Six native species not listed as permissible in the acceptance criteria

Table V Plant species composition and percent cover.

Scientific Name[a]	**Common Name**[a]	**% Cover**
Permissible Species[b]		**16.5**
Grasses		15.1
Bromus inermis	Smooth brome	2.2
Pascopyrum smithii	Western wheatgrass	10.0
Thinopyrum intermedium	Intermediate wheatgrass	2.9
Forbs		1.4
Astragalus spp	Milk vetch	0.4
Sphaeralcea spp	Globemallow	*
Shrubs		1.0
Artemisia tridentata	Big sagebrush	0.7
Ericameria nauseosa	Rubber rabbitbrush	0.3
Non-Noxious Weed Species[b]		**0.5**
Kochia scoparia	Mexican fireweed	*
Salsola kali	Russian thistle	0.5
Not Listed as Permissible or Not Permissible[b]		**20.1**
Grasses		16.0
Achnatherum	Indian ricegrass	0.3
Agropyron cristatum	Crested wheatgrass	1.1
Bromus tectorum	Cheatgrass	0.5
Elymus lanceolatus	Streambank wheatgrass	0.7
Elymus trachycaulus	Slender wheatgrass	2.8
Pseudoroegneria spicata	Bluebunch wheatgrass	3.1
Hesperostipa comata	Needle and thread	0.3
Unidentifiable perennial grasses		7.2
Forbs		4.1
Achillea millefolium	Common yarrow	*
Amaranthus blitoides	Mat amaranth	*
Chenopodium album	Lambsquarters	*
Linum perenne	Blue flax	2.6
Medicago sativa	Alfalfa	1.5
Taraxacum officinale	Common dandelion	*
Ground Surface		**68.3**
Soil		30.8
Rock		10.4
Litter		27.1

[a] Scientific and common names are consistent with the USDA Plants National Database (http://plants.usda.gov).

[b] Plant categories are from revegetation acceptance criteria for the Monticello cover.[41]

(Achnatherum hymenoides, Elymus lanceolatus, Elymus trachycaulus, Elymus trachycaulus, Pseudoroegneria spicata, Hesperostipa comata, and Achillea millefolium) should be included as acceptable. The total cover of all native and permissible species, at least 23.7%, is better than expected considering that it occurred during the driest 3 consecutive years on record for Monticello.

Total plant cover remained consistent between lysimeters and years (Figure 4). Green LAI, a better measure of the transpiration potential than percent cover, was significantly greater in 2002 on the less compacted loam (Lysimeter 1) than on the overly compacted clay loam (Lysimeter 2). Greater transpiration loss may partially explain the seasonally lower water storage values and consistently greater water storage capacity of the less compacted loam. As an apparent anomaly, productivity was highest on Lysimeter 2 in 2003, possibly attributable to the combination of a wet late summer, different species composition, and a later sampling date in 2003. Much of the high 2003 biomass on Lysimeter 2 is thick-stemmed alfalfa (Medicago sativa) that re-greened following late summer rains.

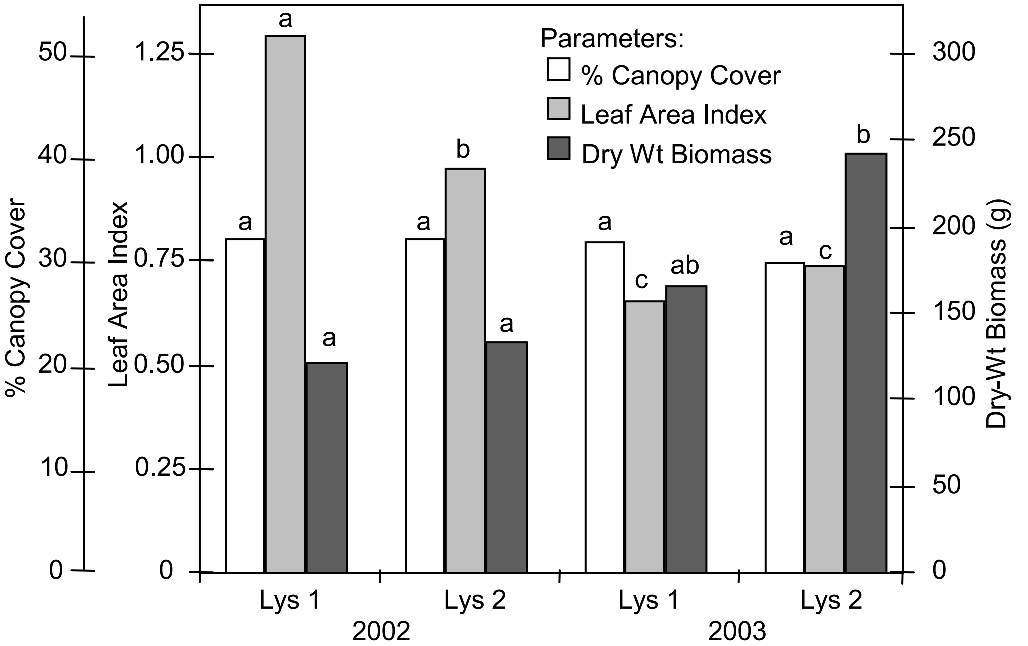


Figure 4. Percent cover, green LAI, and annual dry-weight biomass (productivity) comparing Lysimeters 1 and 2 in 2002 and 2003. Within-parameter bars with the same letter are not significantly different ($P < 0.05$).

SUMMARY

Two large drainage lysimeters fabricated of steel caissons lined with HDPE were installed to evaluate the hydrological and ecological performance of an alternative engineered cover constructed in 2000 on a uranium mill tailings disposal cell at the Monticello, Utah, Superfund Site. The hydrological performance of the Monticello design relies on the water storage capacity of a 163-cm soil "sponge" layer overlying a capillary barrier of fine gravel and sand, to retain precipitation while plants are dormant, and on native vegetation to seasonally remove precipitation during the growing season. The sponge layer consists of a clay loam subsoil compacted to 1.65 g/cm^2 in one lysimeter and a loam topsoil compacted to 1.45 g/cm^2 in the other lysimeter, the range of conditions existing in the nearby disposal cell cover.

About 0.1 mm of drainage occurred in both lysimeters before they were planted during an average precipitation year, an amount well below the EPA target of <3.0 mm/yr. However, the cover with the less compacted loam sponge had a 40% greater water storage capacity than the cover with the overly compacted clay loam sponge. The difference is attributable in part to higher green leaf area and water extraction by plants in the loam topsoil. The lesson learned is that seemingly subtle differences in soil types, sources, and compaction can result in salient differences in performance, especially during wet years. Diverse, seeded communities of predominantly native perennial species were established on both lysimeters during an extended 3-yr drought, highlighting the importance of a sound understanding of the local ecology and of implementing the science and methods of disturbed-land revegetation.

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FOOTNOTES

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