Short and Long-term Fire Impacts on Hanford Barrier Performance - 9449

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ABSTRACT

A critical unknown in long-term engineered barrier use is the post-fire hydrologic function where institutional controls are in-tact but there are no resources to implement maintenance activities such as re-planting. This objective of this study was to simulate wild fire on an engineered barrier at the Hanford Site and document the post-fire changes in barrier performance. Soil physical, chemical, and hydrologic conditions; plant floristics and density; and animal use were characterized pre- and post-burn. Fuel load on the surface ranged from 4.7 to 5.71 tons/acre. Fire was initiated by drip torch and measurements of flame height and temperature were made at nine locations on the barrier surface. Flame heights exceeded 30 ft and temperatures ranged from 250 ^{o}C at 1.5 cm below the surface to over 700 ^{o}C at 1 m above the surface. Soil organic matter, soil wettability, and hydraulic conductivity all decreased significantly relative to pre-fire conditions. Post-fire samples showed an increase in major soil nutrients, pH, and electrical conductivity measured in 1:1 extracts whereas organic matter decreased. Decreases in wettabilty and organic matter are indicative of conditions more conducive to runoff and soil loss. The results of this study will contribute to a better understanding of post-fire recovery in a post-institutional control environment. This should lead to enhanced stakeholder acceptance regarding the long-term efficacy of ET barriers. This study will also support improvements in the design of ET barriers and performance monitoring systems. Such improvements are needed to best meet the long-term commitment to the safe in-place isolation of waste for hundreds if not thousands of years.

INTRODUCTION

A prototype Hanford barrier was deployed over the 216 B-57 liquid waste disposal crib in the former 200-BP-1 (now known as the 200-PW-5) Operable Unit in 1994 to prevent percolation and subsequent transport wastes out of the crib to the underlying groundwater. The 216-B-57 Crib received in-tank solidification (ITS) condensates that were low-level wastes from the 241-BY Tank Farm between February, 1968 and June, 1973. The ITS waste streams were considered suitable for crib disposal and vadose zone infiltration. The barrier is instrumented to monitor its structural stability and components of the water balance to document performance and has been monitored almost continuously for the last 14 years (1,2,3). Monitored components of the water balance including precipitation, surface runoff, water storage, and percolation out of the root zone with evapotranspiration being calculated by difference. The barrier has also been monitored to document plant floristics, ground cover by plant species, and indices of animal use. These data have provided good insight into long-term performance of engineered barriers and plant community dynamics from that initially imposed by re-vegetation. However, one of remaining sources of uncertainty is barrier response to fire.

A number of researchers have describe the environmental effects of wild and prescribed fire in forest ecosystems (4,5), shrublands (6) and grasslands (7). Many of these studies document fire characteristics under different fuel loadings and environmental conditions but highlight a large knowledge gap on the effects of wildland fires on engineered ecosystems. Research on the effects of wildfire has focused mostly on natural ecosystems with essentially no attention to engineered systems like surface barriers. Observations of wildland fire show a spectrum of severities depending on intensity, duration, fuel loading, vegetation type, fire climate, soil type, antecedent soil moisture conditions, and the area burned. The prototype Hanford barrier covers a relatively small area (2.5 ha) and was artificially vegetated at a density atypical of natural shrub steppe ecosystems. Thus, the response of such a system to fire remains largely unknown and is difficult, if not impossible, to extrapolate from observations of natural ecosystems. It is known that most fires, independent of severity and intensity, can cause top kill in most plant species. Alterations to the plant community can cause changes in biomass productivity, evapotranspiration rates, microbial composition, carbon sequestration, and in animal habitat. Post-fire colonization by plants and animals can also be impacted. A number of species can survive fire and initiate post-fire re-growth from subsurface tissue making them attractive for revegetation of engineered barriers. Such species must be identified for the type of barriers being considered for Hanford conditions.

In addition to changes in the plant community, fire has been shown to alter a variety of soil properties. Soil physical properties such as aggregate stability, pore size distribution, water repellency, soil erosivity, infiltration capacity, water storage capacity, and macroporosity have been shown to undergo changes. Fire can alter geochemical properties including pH, nutrient availability, and C:N ratios. Surveys of mixed forests after severe burns have shown thermal alterations to soil that correlate well with differences in fuel load. Deposits of white ash, composed largely of calcite have been observed, covering as much as 25% of the land surface, in places where coarse fuel items were fully combusted (4). A common effect is a change in soil color from the yellow brown characteristic of goethite to reddish colors of maghemite and hematite accompanied by an increase in magnetic susceptibility (4). Changes in silicate mineralogy have also been observed and include the decomposition of kaolin and the dehydroxylation and collapse of vermiculite and chlorite. Changes in mineralogy can be expected to affect soil structure and ultimately hydraulic properties.

The preceding review identifies several issues related to the impact of fire on natural ecosystems that are or relevance to the function of engineered barriers. However, even in the ecosystems that have been studied, the ability to describe or predict impacts of fire is limited due to inconsistent data. This study was conceived to bridge the gap in knowledge on the effects of fire in engineered ecosystems. Not only is this information important to an improved understanding of the impacts of fire on the ability of barriers to mitigate percolation into underlying waste but it is needed to increase acceptance by stakeholders and regulators. Vegetation dynamics can be severely disrupted by fire therefore plant invasion and succession are key considerations in the post-closure institutional control that is so critical to barrier acceptance. This is because the nature of the vegetative cover plays an important role in the post-fire barrier response under extreme precipitation and erosive events. The impact of such events is another source of uncertainty especially if site maintenance and operational funding is lost for activities such as barrier revegetation. The resulting data are also needed to optimize design of barriers, their monitoring systems. Installation strategies are needed to protect electronic equipment from the intense heat of fire and the potential damaging effects of smoke and fire extinguishing agents.

SCOPE AND OBJECTIVES OF THE CONTROLLED BURN

To answer outstanding questions on long-term performance and monitoring, a prescribed burn simulating a wildfire was conducted during the fall of 2008 at the prototype Hanford barrier in Hanford's 200 East Area. The scope of the study was to use a simulated wildfire to induce changes in the ecology, hydrophysical, and geochemical properties of the barrier. The response to these changes would be documented and used to draw inferences about fire behavior under different fuel loadings, fire intensities, and post-fire conditions.

There were three main objectives to this study. The first objective was to characterize barrier conditions before the fire and evaluate preventative measures for protecting barrier monitoring instrumentation against fire damage. The second objective was to document the immediate post-fire conditions and the subsequent re-establishment of vegetation. Immediate post-burn monitoring would focus on quantifying alterations in the soil physical, geochemical, and in plant and animal use. Initial post fire monitoring of vegetative changes would rely on manual methods but would eventually include the evaluation of airborne and remote sensing technologies (e.g., light detection and ranging, hyperspectral imaging) for quantifying changes on the barrier surface.

MATERIALS AND METHODS

Physical Setting

The climate at Hanford is semi arid with cool, wet winters and hot, dry summers with an average of 300 days of sunshine per year. Annual precipitation has averaged 6.85 in (174 mm) since 1946 with almost half occurring in the winter (November through February). The site receives occasional light snow in most years. Temperature ranges from as low as 10 °F (-12 °C) in the winter to as high as 115 (46 °C) in the summer. Humidity ranges from 75% in winter to 35% or less in the summer. Actual evapotranspiration (AET) ranges from 4.4 in. (11.1 cm) to 6.3 in. (159 mm) whereas potential evapotranspiration (PET) ranges from 29.5 in. (750 mm) to 54.7 in. (1390 mm). Winds periodically exceed 30 mph. Glaciofluvial deposited soils are generally coarse in nature (coarse loamy sand to sandy loam) and in some areas of Hanford's Central Plateau form a vadose zone that is over 100 m (300 ft) thick.

The Prototype Hanford Barrier

The barrier design consists of a 2-m thick silt-loam layer overlying other, coarser materials including sand, gravel, and basalt riprap. Each layer serves a distinct purpose. The silt-loam layer acts as a medium in which moisture is stored until the processes of evaporation and transpiration recycle any excess water back to the atmosphere. The design storage capacity, the total amount of water that can be stored in the silt-loam layer before drainage occurs, is 600 mm. The silt loam is designed to store more than three times the long-term average annual precipitation at the Hanford Site. The silt loam also provides a medium for establishing plants, which are necessary to recycle water to the atmosphere. In addition, the top 1 m of silt loam had been amended with 15% by weight of pea gravel to minimize wind erosion. Coarser materials (sand overlying gravel) placed directly below the silt-loam layer create a capillary break that inhibits the downward percolation of water through the silt and prevents fine soil from migrating downward into the coarse layer. The coarser materials (i.e., basalt riprap) also help deter root penetration, animal burrowing, and inadvertent human intruders (biointrusion) through the barrier profile. An asphalt layer is placed at the bottom of the barrier to provide a low-permeability (hydraulic barrier) and redundant biointrusion layer.

Site Vegetation

The native vegetation at the site was originally a mixture of sagebrush, tumble mustard (*Sisymbrium altissimum*), cheatgrass (*Bromus tectorum)*, Sandberg's bluegrass (*Poa secunda*), bulbous bluegrass (*Poa bulbosa)*. Tumble mustard is a summer annual species with a rooting depth of 1 m or and greater. Cheatgrass is a winter annual species with roots to a depth of around 0.75 m. Surveys of vegetation on the barrier and side slopes have been conducted in the spring and summer months for the last several years on the surface and on the side slopes (3). Variables typically measured include shrub height and canopy dimensions as well as cover of grass, shrubs, forbs, litter, soil, and soil cryptogams. Based on the most recent survey, sagebrush now dominates the shrub cover of the barrier whereas Rabbitbrush is quite sparse (3). The dominance of *A. tridentata* on the surface may likely contribute to continued reductions in species richness on the surface. Figure 1 is a south-facing aerial view of the barrier showing the current distribution of plants on the surface and side slopes. Note the relatively sparse vegetation in the northwest (lower right) quadrant of the surface.

Performance Monitoring

The barrier is instrumented for monitoring components of the water balance (i.e., precipitation,

Figure 1. South Facing Aerial View of Prototype Hanford Barrier Showing Distribution of Plants on the Surface and Sideslopes. North is at the bottom end of the photo, south is at the top. Note the relatively sparse vegetation in the northwest (lower right) quadrant of the surface.

runoff, water storage, and percolation out of the root zone). There are 12 monitoring stations on the barrier and two on the gravel side slope. Surface runoff is monitored with an erosion flume. Water storage is monitored by vertical water content measurements made with a neutron hydroprobe and time domain reflectometry (TDR) sensors. Matric potential and soil temperature are measured by heat dissipation units (HDUs). Percolation is monitored using a system of 12 concrete vaults located to the north and down-gradient from the asphalt layer to allow the movement of water by gravity (1,2). A series of curbs divide the asphalt surface into 12 water-collection zones, the boundaries of which align vertically with the 12 surface plots. Monitoring of deep percolation is facilitated by a 6.5 m by 6.5 m pan lysimeter installed under the northeast section (centered on plot 4E) of the asphalt layer (1,2). Horizontal access tubes are monitored by neutron probe to determine soil moisture content at the capillary break and beneath the asphalt pad. At the west side of the barrier, two pairs of U-shaped, horizontal access tubes were installed at 1.95 m below the surface, near the capillary break (silt loam-sand filter interface). Six minirhizotrons, constructed of clear acrylic tube, were installed on the barrier to measure root distributions.

The barrier was routinely monitored between November, 1994, and September, 1998, as part of a *Comprehensive Environmental Response, Compensation, and Liability Act of 1980* (CERCLA) treatability test (2). Since FY 1998, monitoring has focused on a more limited set of key water balance, stability, and biotic parameters. The 600 mm design storage has never been exceeded. Above-asphalt and below-asphalt moisture measurements show no evidence of deep percolation of water. To date, runoff has been recorded at the barrier on only two occasions, once when the surface was bare, and once after a rapid snow melt on a frozen soils surface (1,3).

Experimental Design

The simulated fire was limited to the north half of the barrier, which was divided into nine 12 × 12 m plots. Each plot was randomly assigned one of two fuel load treatments for the test, depending on the cover density on the plot. Two fuel loads were used in the study, 4.7 and 5.71 tons/acre. A flame height rod was installed in the center of each plot for visual observation of the flame height during the fire. The flame height rods were also served as scaffolds to which thermocouples were mounted for measuring temperature. Type K thermocouples were positioned 1.5 cm below the soil surface, at the surface (0 cm) and at five additional elevations above the surface, 1, 10, 30, 100, and 200 cm. Each of the 63 thermocouples was attached to a HOBO datalogger to record temperatures. Temperatures were measured once per second from about 3 hours before the fire until about 9 hours after the fire. Field monitoring during and after the fire made use of existing surface and borehole geophysical techniques. Moisture content profiles were measured using a MoisturePoint® time domain reflectometry (TDR) with remote shorting diode probes and with a neutron hydroprobe (CPN 503DR-1.5). Not much consideration was given to fire protection during the original installation of the instruments. Thus, it was necessary to prepare all instrument installations for the fire test. This involved covering instrumentation, instrumentation boxes, solar panels, and other infrastructure with fiberglass insulation, aluminum foil or fire blankets and in some cases (e.g. minirhizotrons) fiberglass insulation covered with inverted galvanized pails. Fire blankets and aluminum foil covers were secured around the edges by covering with soil.

Pre-burn Measurements

Prior to the simulated fire, the site was characterized to establish initial conditions. Plant information collected included a species inventory for the entire barrier (north and south sections) and gravel side slopes. Canopy characteristics were measured on 25 individual *A. tridentata* plants on the barrier surface to estimate shrub fuel density. Shrub height, greatest canopy diameter, and the diameter at the center of the plant perpendicular to the greatest diameter were measured on each shrub. Surveys were conducted to characterize density, ground cover, and leaf area index (LAI) on the barrier and side slopes. In addition, surveys were conducted in natural communities (McGee Ranch) on silt loam soils to cover the expected range of densities and ground cover (low, medium, and high). Soil cryptogam type was determined and ground cover estimated. Estimates of LAI were determined for each plot using a LiCor Plant Canopy Analyzer.

Fuel characteristics were determined using a geostatistical sampling scheme as described by Robichaud (8, 9). In addition to fuel characteristics, the biomass of the cover (shrubs and other species) was estimated. These measurements were made on ten individual plants off the barrier surface that covered the range of plant sizes on the barrier surface. These ten plants were then harvested, weighed, dried, and weighed again to calculate the fuel moisture content. Some areas of the barrier surface were quite sparse in vegetative cover (e.g. Figure 1) and required supplemental biomass to ensure representative fire intensities and severities. Supplemental fuel consisted primarily of *Salsola kali* (tumbleweed). Additional tumbleweed biomass was brought onto the surface and loaded onto plots that were lacking in sufficient fuel to carry the fire. Subsamples of the imported fuel were weighed and dried to determine the moisture content. When considering the impact of wildfire, the ability of a plant species to re-sprout after fire and the ability to recruit from persistent seed banks are two of the desirable attributes of an ideal species for revegetation. Thus, the seed bank on the barrier was assessed in each of the 12 ×12 m plots by collecting surface soils and germinating seed in the greenhouse. In order to understand the pattern of small mammal communities within engineered ecosystems altered by fire, the composition, demography, and variation of small mammals and insects on the north half of the barrier were characterized. This involved examination of the barrier surface for evidence of use and intrusion (burrowing) by insects and small mammals.

Soil physical and hydraulic properties were also characterized prior to the fire to establish a baseline. Soil samples were collected at depths 0-5 cm and 5-10 cm on a 3 × 3 m grid to determine the initial near-surface gravel content. This is because changes in the surface layer composition may be expected following a fire that removes the vegetation and surface litter that protects the soil surface from raindrop impact and erosion by water and wind. Samples were sieved through a 2-mm sieve and the < 2 mm fraction used to characterize geochemical properties including soil pH, cation exchange capacity, specific surface area, and concentrations of macro nutrients (e.g. N, P, K) and other elements such as Na, Mg, and Ca. Hydraulic conductivity was measured on the 9 × 9 m grid using a Guelph Permeameter (10) and Guelph tension infiltrometer (11). Use of the tension infiltrometer measurements required that the soil surface be leveled prior to measurement. Water drop penetration time tests were performed on the 9 × 9 m grid to determine wettability (12). Near-surface moisture content and bulk density were measured on a 3 × 3 m grid using a Troxler 3440 surface moisture-density probe.

Simulated Fire

The ground fire crew used drip torches in a sweeping fashion starting at the center of the southern portion of the northern half of the barrier and worked east and west along the southern portion and north allowing the flames to carry eastward. All three fire ground crew maintained constant radio contact with the fire rigs. Progress of the fire was documented using still photographs and a digital video camera configured to view the entire burn area. During the fire, flame height was measured by recording elevation of the flame on flame-height rods mounted within each plot. Flame height rods were observed using binoculars. Fire intensity is a good indicator of above-ground fire effects such as scorching height and other biological impacts (13, 14). Fire intensity was determined from temperature measurements made at the center of each of the nine 12 × 12 plots using thermocouples. The thermocouples were installed at different elevations above the surface by mounting on flame height rods. The controlled burn involved multiple organizations including the U.S. Department of Energy (DOE), Hanford Fire Department (HFD), the Pacific Northwest National Laboratory (PNNL), the former Fluor Hanford (FH), former Fluor Government Group (FGG), and Washington State University (WSU).

Post-burn Measurements

Following completion of the fire, most of the pre-burn measurements were repeated. Soil samples were collected on the 3 × 3 m grid and the physical, hydraulic, and geochemical measurements repeated. Water extracts (1:1) were used to measure soil pH, electrical conductivity, as well as the concentrations of macro nutrients. Measurements of cation exchange capacity and specific surface area were repeated on the < 2 mm fractions whereas water drop penetration tests were performed on whole samples. Gravel content was determined by dry sieving. Hydraulic conductivity measurements were repeated on the 9 × 9 m grid using the Guelph Permeameter and Guelph tension infiltrometer methods. Near-surface moisture content and bulk density were repeated on a 3 × 3 m grid. Soil samples were also collected on a 12 ×12 m grid to assess the seed bank remaining after the fire.

Data Analysis

The experiment was designed to allow analysis of spatial and temporal changes using geostatistical techniques. However, for the purpose of this paper, changes are quantified using simple statistical methods. The two-sample paired t-test was used to determine the statistical significance of differences between pre-burn and post-burn measurements. The two-sample paired t-test compares the null hypothesis that the population mean of the paired differences of two samples is zero,

$$H_0 : \mu_1 = \mu_2 \quad \text{(Eq. 1)}$$

The alternate hypothesis, that the two means are different is written as:

$$H_1 : \mu_1 \neq \mu_2 \quad \text{(Eq. 2)}$$

Paired samples often occur in pre-test/post-test studies in which variables are measured before and after a treatment. Pairing matches up measurements for the pre- and post-burn sampling to minimize their dissimilarity except in the factor (i.e., effect of fire). The level of significance used in the two-tailed tests is 0.05. The relevant test statistic is, $\bar{t}$ (t_{crit}) given by:

$$\bar{t} = \frac{\bar{x}_1 - \bar{x}_2}{\sqrt{S_w^2\left(\frac{1}{n_1} + \frac{1}{n_2}\right)}} \quad \text{(Eq. 3)}$$

where *n* is the sample number in each population and S_w^2 is the pooled variance given by:

$$S_w^2 = \frac{(n_1 - 1)S_1^2 + (n_2 - 1)S_2^2}{n_1 + n_2 - 2} \quad \text{(Eq. 4)}$$

The two-sample paired t-test is appropriate for this study because measurements were made at the same locations pre-burn and post-burn. Note that this t-test does not assume that the variances of both populations are equal. For temperature measurements, mean temperatures were computed for each height and are presented with one standard error of the mean.

RESULTS AND DISCUSSION

Pre-burn Plant and Animals

Prior to the burn, plant species observed on the burned half of the surface were *Artemisia tridentata* (Big sagebrush), *Bromus tectorum* (Cheatgrass), *Elymus wawawaiensis* (Snake River wheatgrass), *Ericameria nauseosa* (Gray rabbitbrush), *Machaeranthera canescens* (Hoary aster), *Poa secunda* (Sandberg's bluegrass and Sherman big bluegrass), and *Salsola kali* (Tumbleweed). Sagebrush dominates the shrub cover on the surface whereas Gray rabbitbrush is quite sparse, concentrated mostly near the edges of the surface. Overall, vegetation was quite sparse in the northwest quadrant of the surface suggesting a need to import fuel.

The species richness of the surface has decreased from a high of 35 species in 1997, the third year after planting, to only 12 in 2008. Only seven of 14 species present in 2004 were present in 2008. Of the five new species on the surface in 2008, *Centaurea diffusa* has never been present while the other four have been observed in the past (3). The dominance of *A. tridentata* on the surface may likely contribute to continued reductions in species richness on the surface. Many of the species present at the pre-burn survey are represented by only a few individuals and some of these were only found on the edges of the surface where there is less competition from *A. tridentata*. The reduction in the number of species on the surface is partly caused by a relatively high density of *A. tridentata*. *Artemisia tridentata* was by far the most common plant on the surface and comprises almost a monoculture. This in itself is somewhat undesirable as if the shrubs were to die in a pathological event or if the area were to burn, it is unlikely that other species would immediately colonize the available space which could reduce evapotranspiration.

Biomass was estimated across the surface by assessing *A. tridentata* and *S. kali* litter. The canopy structure of *A. tridentata* was measured and related to harvested biomass. Measures were taken on 18 plants covering the range of sizes on the barrier surface. The measures taken were the greatest height (*z*), the greatest diameter (*x*), and the greatest diameter 90° to the greatest diameter (*y*). These individuals were then harvested and weighed. The relationship used to predict biomass is:

$$B = \alpha + \beta e^{(\gamma x + \delta y + \varepsilon z)} \quad \text{(Eq. 5)}$$

where α, β, γ, δ, and ε are nonlinear regression parameters. The estimated parameters (Table 1) resulted in a highly significant predictive relationship ($r^2 = 0.95$, $p < 0.001$). The parameter values are α = -182.3 ±144.1, β = 129.0 ±100.5, □ = 0.01239 ± 0.006033, δ = 0.007617 ± 0.004571, and □ = 0.003688 ± 0.002629.

Eighty one *A. tridentata* shrubs were measured for canopy characteristics across the burn area resulting in an average predicted wet biomass of 522 ± 55 g. Shrubs were counted in 84 quadrats resulting in an average of 13.15 ± 0.65 shrubs in each quadrat. Thus, there were about 1,894 shrubs on the surface with a total estimated wet biomass of 988 kg. The mean water content was 22.4 ± 0.87 % by weight, thus the oven dry biomass was 767 kg or 0.845 tons. There was about 0.423 tons of oven-dried shrub mass in each of the high- and low-fuel treatments on the surface. The area of the burn area is 0.32 acres so the mean shrub fuel load was around 2.64 tons $acre^{-1}$.

The biomass of *S. kali* was determined by estimating the amount present and the amount added to the surface. The amount added to the surface was similar to amounts already present in the low-fuel treatments, but was distributed fully across the surface while that already present was clumped. The average wet mass added to the low-fuel treatment was 3.67 kg in each quadrat. The mean water content was 4.21 ± 0.327 % resulting in an oven-dry biomass added of 3.52 kg. About 253.6 kg or 0.28 tons of oven-dried mass was added to low-fuel treatment. The added fuel load was about 1.75 tons $acre^{-1}$. The average wet mass added to the high fuel half was 5.51 kg in each quadrat. Thus, the oven dried biomass added was 5.29 kg. There was about 380.7 kg or 0.42 tons oven dried mass added to the high fuel half. The added fuel load is about 2.63 tons $acre^{-1}$.

The mass already present in the low-fuel treatments was estimated by relating the mass of added fuel that provides generally high cover of about 90% to existing cover in each quadrat. The cover was visually estimated in each quadrat. The resulting estimate is 0.63 ± 0.08 kg in each quadrat. There was about 45.4 kg or 0.05 tons existing in the low fuel half of the surface. The existing fuel load is about 0.31 tons $acre^{-1}$. The existing biomass on the high-fuel treatment was estimated at 1.31 ± 0.14 kg in each quadrat. There was about 94.3 kg or 0.104 tons existing in the high-fuel treatment. The existing fuel load was about 0.65 tons $acre^{-1}$. The total fuel load on the low-fuel plots was around 4.7 tons $acre^{-1}$ com pared to 5.71 tons $acre^{-1}$ on the high-fuel plots. The fuel load contributed by bunchgrasses and other plants was minor and was not used for the total fuel load estimate.

The important ecological role of small mammals, along with their ubiquitous nature, makes them important tools in clarifying and comparing the effects of fire on habitat change (15). To understand the pattern of small mammal communities within engineered ecosystems altered by fire, the composition, demography, and variation of small mammals and insects on the north half of the barrier were also examined. Pre-burn surveys were conducted across the entire surface to document evidence of use and intrusion (burrowing) by insects and small mammals. Small mammal traps were used to positively identify vertebrates on the surface. Evidence of animal use was observed on the surface and included direct observation (traps), the presence of droppings, tracks, nests, burrows, holes, and resting spots. The most common mammal found on the surface by trapping was deer mice (*Peromyscus* sp.).

Pre-burn Soil Properties

Pre-burn soil physical and hydraulic properties were measured on soil samples and in the field to establish the initial conditions. The results of these analyses are summarized in table I. An important phenomenon affecting infiltration or water movement in soils is the hydrophobization of originally wettable mineral particles by coatings of organic substances of different origin (16). Changes in hydrophobization can change the wettablility, which has been shown to have a strong impact on water movement, particularly on infiltration and, therefore, surface runoff. Wettability was measured on whole and sieved samples used for determining gravel content. All of the preborn samples showed a water drop penetration of less than 5 seconds and were therefore characterized as wettable. The top 1-m consists of a 15% pea gravel silt loam admix as a protection against erosion. Quantifying gravel content is therefore one means to quantify inflationary or deflationary responses to fire and to reveal the ability of the surface to resist post-fire erosive stresses. Near-surface soil samples (0-2 cm, 0-5 cm) were collected and analyzed for gravel content. The mean gravel content prior to the fire was 20.1 %, compared to the original 15%, which may be indicative of deflation over the last 14 years.

Estimates of hydraulic properties were derived from in situ measurements of hydraulic conductivity using the Guelph permeameter, with one-head and two-head analyses, and with the Guelph tension infiltrometer. Both methods allowed calculation of the alpha parameter, which is the inverse of the bubbling pressure. The mean pre-burn alpha was 0.085 cm^{-1}, which is equivalent to an air entry pressure of about 12 cm. This value is somewhat small for a silt loam but is consistent with a field soil with well developed structure including the presence of macropores and is likely influenced by the gravel in the near-surface. Field measurements of the hydraulic conductivity (K(ψ)) is necessary for characterizing

Table I. Effect of Fire on Soil Physical and Hydraulic Properties

Variable	**Sampling**	**Mean**	**Variance**	**Df**	t_{stat}	**P(T<=t) two-tail**	t_{crit} **two-tail**
Penetration Time (s)	Pre-burn	5.000	0.000	34	-3.812	0.001	2.032
	Post-burn	14.394	260.279				
Gravel Content (%)		0.201	0.003	279	-0.646	0.519	1.969
		0.205	0.004				
[a]alpha (1/cm)	Pre-burn	0.085	8.95E-04	10	1.284	0.228	2.228
	Post-burn	0.068	3.27E-04				
[a]K_{fs} (cm/s)	Pre-burn	1.33E-03	1.24E-07	6	4.038	0.007	2.447
	Post-burn	7.88E-04	2.55E-10				
[b]K_{fs}(cm/sec)	Pre-burn	1.27E-04	8.52E-10	2	0.128	0.910	4.303
	Post-burn	1.24E-04	6.86E-10				
[c]K_{fs}(cm/sec)	Pre-burn	4.31E-04	1.02E-07	2	0.787	0.575	12.706

	Post-burn	2.35E-04	2.21E-08				
Surface Area (m^2/g)	Pre-burn	9.915	0.003	7	3.609	0.009	2.365
	Post-burn	7.372	3.969				
(a) Guelph permeameter measurement; (b) Guelph permeameter, one-head measurements, (c) Guelph permeameter, two-head measurements							

many aspects of unsaturated water flow including infiltration and runoff. Estimates of the field-saturated hydraulic conductivity, K_{fs}, derived from the tension infiltrometer showed a mean of 1.33×10^{-3} cm/s with a standard error 0.009. This value is roughly one order of magnitude larger than the saturated hydraulic conductivity measured in laboratory on repacked on silt loam samples prior to construction of the barrier. The one-head and two-head K_{fs} measurements made with the Guelph permeameter are remarkably similar given the variability typically found in hydraulic conductivity measurements. Nonetheless, these data provide a good reference point for quantifying the effects of fire. Specific surface area, which controls sorption and the hyper-dry region of the moisture retention function, was also measured. As shown in Table I, the mean value for the surface soil, sieved to pass a 2 mm sieve, was 9.915 m^2/g. This value compares well with independent measurements that range from 8 to 11 m^2/g.

In addition to physical and hydraulic properties, the soil geochemical properties were also characterized prior to burning. Measurements were made to determine organic matter content, pH, cation exchange capacity, electrical conductivity, which is related to total dissolved salts, and nutrient availability. These results are summarized in Table II. Hanford sediments are typically low in organic matter and the same is true for the barrier soils. The mean pre-burn organic matter content was 0.916 ±0.03 %. The soil was slightly basic with a pH of 8.036 whereas CEC averaged around10.3 meq/100g. Nitrate in the form of ammonium was only 4 mg/kg in the pre-burn samples whereas nitrogen in the form of nitrate was 3.6 mg/kg; phosphorus and potassium contents were 11.38 and 239 meq/100 g, respectively. All of these measurements were repeated on post-fire samples to quantify the effects fire on soil properties.

Simulated Fire

Weather conditions on the day of the burn were sunny with a mean temperature of 75 ^{o}F and a slight wind from the South to the North. Prior to the fire, a foam line was established to separating the area to be burned (north half) form the area to that would be left unburned (south) half. The fire was ignited at 3:15 PM by three ground fire crew. The fire on top of the barrier was fast moving with flames reaching as high as 30 feet. Flame heights exceeded the 20-ft flame height rods but were estimated using video records with near-by infrastructure being used as a scale. The fire lasted approximately seven minutes by which time all of the imported fuel and most of the natural biomass had been consumed. Not all of the vegetation near the edges of the barrier was initially consumed. The fire ground crew revisited unburned areas and ignited un-burnt or partially burnt plants with drip torches. The lower burn efficiency around the edges of the barrier may be related to the size and moisture content of the biomass. Plants around the edges of the barrier were typically bigger, perhaps due to a larger amount of available moisture that accumulates at the capillary break near the edge (3). The on-duty fire captain concluded that based on the fuel load, flame height, and intensity of the flame, the prescribed burn mimicked a large-scale wild-land fire of over 2000 acres. After the burn, the surface was examined and to identify any mosaic patterns that might be indicative of variable fire severity. A thick, white crust of ash had formed across most of the site with large accumulations where larger shrubs were resident.

The time-course of temperature before, during, and after the fire was recorded with HOBO data loggers and examples of these data are shown in Figure 2. These two temperature time-courses were taken from one tower at the hottest part of the barrier surface. Temperatures ranged from 250 ^{o}C at 1.5 cm below the surface to over 700 ^{o}C at 1 m above the surface. Results data show that the air temperature rose much higher than the soil temperature. This can be expected because of the large amount of fuel on the surface and the flame heights. In addition, the thermal conductivity of soil is strongly dependent on moisture with dry soils being very poor thermal conductors. With little soil organic matter, the only other possible source of fuel in the subsurface would have been live roots and as a result there would have been little transmission of heat in the subsurface. After the peak temperature was attained, air temperature also fell off much more rapidly than the soil temperature. The effect of the fire on soil temperature persisted from for about two hours (Fig. 2). These differences can again be attributed to differences in thermal conductivity between the soil and air and differences in the effects wind circulation on the redistribution of heat.

Soil and air temperatures measured at the nine towers were used to generate contour plots of the spatial distribution of temperature above and below the surface. Figure 3 shows a plot of peak temperatures recorded across the burnt area. Both air temperature (Fig. 3a) and soil temperature (Fig. 2b) maps show that the highest temperatures were recorded in the plots with the higher fuel load, e.g., between x=3 and 7 m in Figure 3. The fire did not burn across the gravel access road that surrounds the top of the barrier, thus the gravel acted as a natural fire break. The toe of the gravel side slope did not burn very well, perhaps due to the high moisture conditions of the plant biomass and the low plant density that resulted in large open areas between plants. Basically the fire consumed only the plants that were lit by the drip torch but did not transfer between plants. Winds were also very mild and did not play a major factor in transporting the fire from plant colony to colony, with one exception. A post-fire site inspection found all instrumentation to be in working order and with no evidence of fire damage.

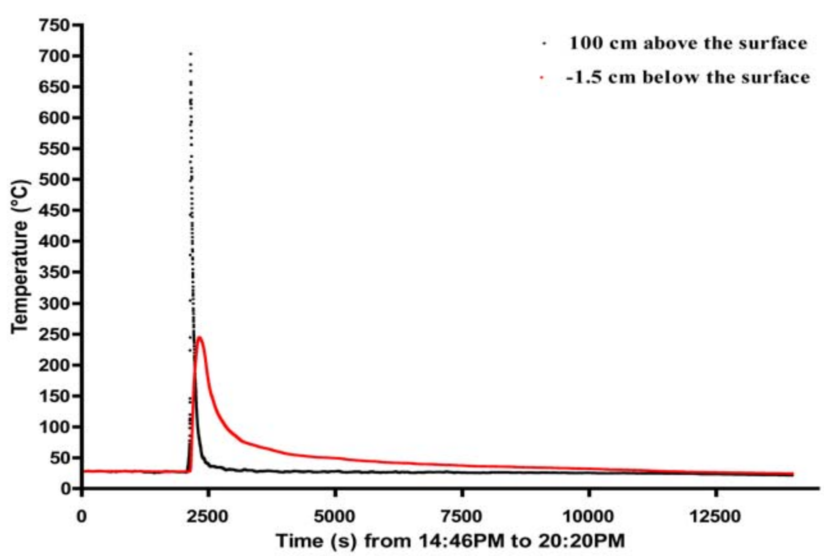

Figure 2. Temperature in the air and soil before, during, and after the fire.

(a)	(b)

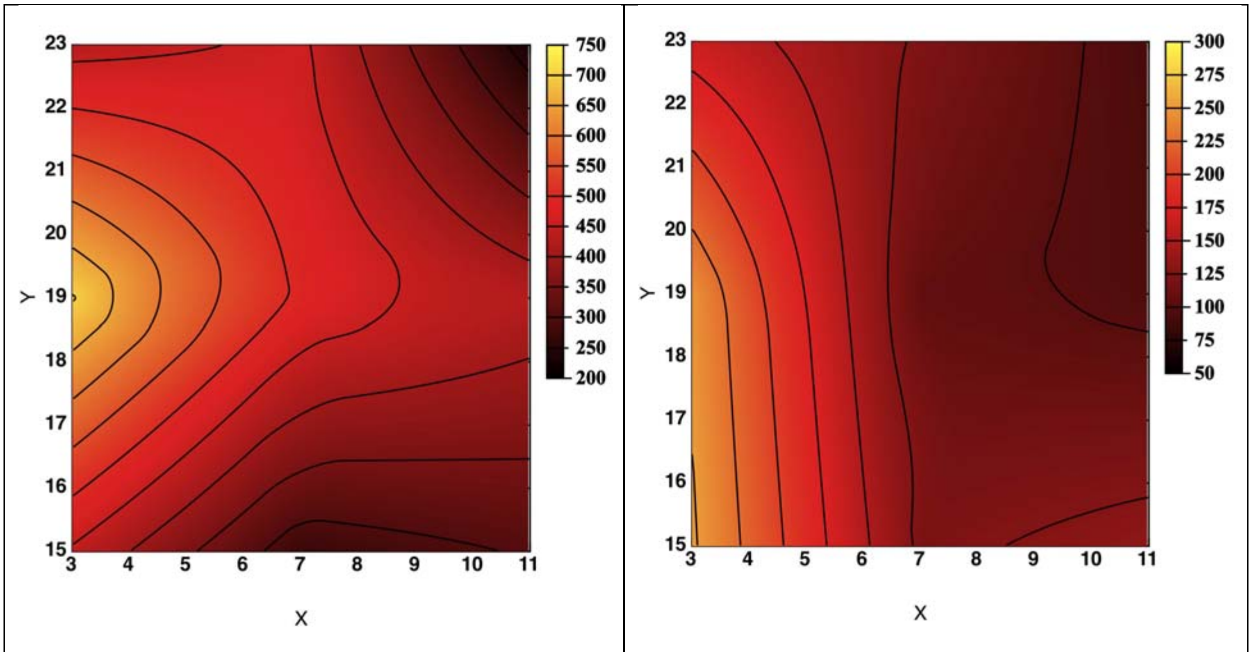

Figure 3. Peak temperatures observed on the burnt section of the barrier, (a) air temperature measured 100 cm above the surface, and (b) soil temperature measured 1.5 cm below the surface on the burn area. The unit of temperature is degree Celsius.

Post-burn Soil Properties

Soil samples were collected from the site within two days of the fire and analyzed to determine physical and hydraulic properties, including near surface gravel content, particle size distribution, and wettability. These samples were also used to characterize the major nutrients and geochemical properties including pH, organic matter, and electrical conductivity on 1:1 water extracts following the same protocol as in the preborn analyses. Pre-burn and post-burn results were compared using the paired t-test described previously. Table I summarized the changes in soil physical and hydraulic properties between the initial condition and the post-fire sampling.

Table I shows a dramatic increase in the water drop penetration time following the fire. Penetration time increased from less than 5 seconds to mean of 14.4 s with a standard error of 2.7. Penetration times of over 160 s were observed, which is indicative of a soil that is strongly water repellant. The paired t-test resulted in a t_{stat} value of -3.812, which is larger than the critical values of 2.032 therefore we must reject the null hypothesis that there is no difference between the pre- and post water drop penetration times, i.e., there was a significant increase in water repellency in response to the fire. Post fire gravel content was only 20.5%, not significantly different from the pre-burn value. This result is not surprising as significant changes in near-surface gravel will only occur after inflationary (soil blowing in) or deflationary (soil loss) events and no such events had occurred by the time of sampling.

Estimates of the alpha parameter decreased slightly from the pre-burn value, suggesting an increase in bubbling pressure or a decrease in coarseness of the soil texture. This result is not surprising given the increase in content of ash and other fines relative to the initial condition. However, the change was not statistically significant. In all cases, the K_{fs} decreased relative to the pre-burn condition. The calculated t_{stat} was greater than t_{crit} for K_{fs} measured by tension infiltrometer, suggesting a significant reduction on K_{fs} following the burn. However, K_{fs} measured by the

Guelph permeameter showed no significant change. These results are consistent with the measurement methods. The infiltrometer measurement is essentially a surface measurement and would be strongly influenced by surface changes in ash and organic matter content. In contrast, the permeameter measurement is made in a 15-cm deep hole where soil properties would be expected to show very little change due to the fire. In all cases, the measured post-burn values of K_{fs} were of the same order of magnitude as that measured in laboratory on repacked on silt loam samples prior to construction of the barrier. Thus, the fire appears to have destroyed the mechanism that led to an increase in near-surface K_{fs}. Specific surface area decreased from a mean of 9.9 m^2/g to 7.3 m^2/g. The calculated t_{stat} was out side the range of t_{crit}, indicating that the null hypothesis should be rejected. A significant decrease in surface area is not surprising as the fire would be expected to bring about changes in organic matter content that contributes to higher surface area.

Post-burn geochemical properties and their changes relative to pre-burn conditions are summarized in Table II. The mean post-burn organic matter content showed a significant increase from conditions prior to the fire. This result is a little counter intuitive but may be a reflection of the measurement method which digests the soil sample. Measurements of organic matter by the combustion method actually showed a decrease. Published reports suggest that high temperatures generated by wild fire can remove virtually all near-surface soil organic matter thereby altering the cation exchange capacity of the soils. These types of changes have been observed as deep as 80 mm (4). Soil pH increased significantly from 8.0 to 8.98. The availability of many nutrients is also very sensitive to changes in pH, which has been shown to change following wildfire. In fact, soil pH and cation nutrients have been reported to increase immediately following burning (17, 18, 19) with the effect typically remaining for one to several years. Soil CEC measured on pre- and post-burn samples did not show any significant difference. However the electrical conductivity of 1:1 water extracts increased significantly. This can be expected as fire is known to increase the availability of nutrients and therefore total dissolves salts that would directly impact the electrical conductivity. The effect of pH and increased nutrient availability due to the break down of plant biomass is evident in the analyses for N, P, and K. Nitrogen in the form of ammonium increased significantly from 4.0 mg/kg to 15.5 mg/kg, an indication of the breakdown of typically indigestible plant tissue. Nitrogen in the form of nitrate also increased significantly although the change was not as large as the case of ammonium-N. This is indicative of an N-limiting environment in which most of the N is tied up in plant tissue. Phosphorus, based on bicarbonate extract was more than doubled, increasing from 11.4 meq/100 g to 26 meq/100g. Potassium also increased significantly from 240 meq/100g to 380 meq/100 although changes in calcium and sodium were insignificant; magnesium content increased by a factor of almost two to show a significant change.

SUMMARY AND CONCLUSIONS

A critical unknown in long-term engineered barrier use is the post-fire hydrologic function where institutional controls are in-tact but there are no resources to implement maintenance activities such as re-planting. A study was recently conducted at the Hanford Site to gain insight into the effects of wild fire on the short-term and long-term function of an engineered barrier. A controlled burn was used to remove vegetation from the northern half of a 2.5 ha barrier and the test was successful. Flame heights of over 30 ft were observed and temperatures ranged from 250 ^oC at 1.5 cm below the surface to over 700 ^oC at 1 m above the surface. Soil physical, chemical, and hydrologic conditions; plant floristics and density; and animal use were characterized pre- and post-burn. Results complied within the first two months of post-fire monitoring show significant changes in soil properties that can be attributed to the fire and that could affect both long-term and short-term barrier performance.

At the conclusion of this study, it is anticipated that there will be an enhanced improvement in demonstrating future barrier performance and the application of barrier construction design modifications (if warranted). Furthermore, it is anticipated that the three tiered process of developing the capability of monitoring barrier performance remotely will not only result in a large cost-savings to the taxpayers, but will also improve the overall confidence in barrier performance. Lessons-learned for long-term monitoring instrumentation including the type, protection, and placement of instrumentation, will enhance monitoring reliability and concurrently reduce overall life-cycle costs.

The combination of barrier design modifications and barrier performance monitoring theoretically should lead to reductions in barrier maintenance costs. And finally, paramount to this study, major reductions in long-term barrier performance uncertainty will be realized. These results are anticipated to improve stakeholder acceptance regarding the long-term efficacy of barriers as a viable remedial action alternative. In addition, changes in barrier design, modifications to barrier monitoring, and an improved understanding of barrier plant dynamics will useful in tackling this long-term commitment to society of leaving waste in-place for hundreds if not thousands of years. The site will also prove useful as a test bed to evaluate airborne and remote sensing technologies for monitoring vegetation dynamics as the surface is revegetated and perhaps overall barrier performance.

Table II. Effect of Fire on Soil Geochemical Properties

Variable	**Sampling**	**Mean**	**Variance**	t_{stat}	**P(T<=t) two-tail**	t_{crit} **two-tail**
Organic Matter (%)	Pre-burn	0.916	0.053	-5.449	4.11E-06	2.030
	Post-burn	1.256	0.105			
pH (s.u.)	Pre-burn	8.036	0.046	-12.520	1.74E-14	2.030
	Post-burn	8.978	0.147			
CEC (meq/100 g)	Pre-burn	10.323	0.0023	-0.3979	0.7025	2.365
	Post-burn	10.4	0.291			
Electrical Conductivity	Pre-burn	0.189	0.001	-15.905	1.37E-17	2.030
(mmho/cm)	Post-burn	0.493	0.012			
Ammonium-N (mg/kg)	Pre-burn	4.050	9.693	-12.477	1.93E-14	2.030
	Post-burn	15.511	20.559			
Nitrate-N (mg/kg)	Pre-burn	3.622	3.461	-3.464	0.001422	2.030
	Post-burn	5.206	2.821			
P-Bicarbonate (meq/100 g)	Pre-burn	11.389	17.787	-9.844	1.28E-11	2.030
	Post-burn	26.028	49.056			
K-Bicarbonate (meq/100g)	Pre-burn	239.750	4276.250	-7.589	6.75E-09	2.030
	Post-burn	380.472	12136.599			
Calcium	Pre-burn	17.508	0.646	-0.935	0.356426	2.030
	Post-burn	17.692	0.645			
Magnesium	Pre-burn	1.409	0.027	-2.479	0.018127	2.030
	Post-burn	2.686	9.328			
Sodium	Pre-burn	0.054	0.001	-1.953	0.058824	2.030
	Post-burn	0.095	0.015			

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