Fire Impacts on an Engineered Barrier's Performance:

The Hanford Barrier One Year After a Controlled Burn – 10472

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ABSTRACT

A critical unknown for long-term engineered barrier performance is the effect of wild fire during a post-institutional control environment where routine maintenance may be limited or non-existent. In September 2008, a controlled burn was conducted on one half of a vegetated, multilayered capillary barrier emplaced over a Hanford waste site. The effects on barrier performance have been monitored and documented over the past year. Soil physical, chemical, and hydrologic properties; plant floristics and density; and animal-use were characterized before and after the fire with the unburned half of the barrier serving as a control. Temperatures during the controlled burn ranged from 250 °C 1.5 cm below the surface to over 700 °C, 1 m above the surface. Significant decreases in hydraulic conductivity and surface-soil wettability were observed immediately after the fire. Post-fire concentrations of major soil nutrients, pH, and electrical conductivity remain elevated. Dense stands of sagebrush were destroyed from the fire allowing many more species to emerge, thereby increasing species diversity. Seed sources contributing to this species diversification were from either the existing seedbank and/or wind-blown sources. There were significant differences in the rate of accumulation and loss of soil moisture on the burned and unburned sections. On the burned section, water storage was higher during the fall; it increased more slowly with the onset of winter precipitation (owing to higher evaporation); and it decreased more slowly in the spring (owing to lower evapotranspiration). There were significant differences in storage between the burned and unburned sections by end of October 2009 although barrier effectiveness has not been compromised.

INTRODUCTION

Enhanced capacitive covers combine natural or modified soil materials with evapotranspirative surface layers to control infiltrating surface water. They are now accepted as an alternative to the removal, treatment, and disposal of near-surface contaminants in arid and semiarid regions where potential evapotranspiration (PET) significantly exceeds precipitation. Over their functional life, barriers will be subjected to extreme events including erosive stresses and abnormal precipitation events. On bare surfaces, such as those which may result from wildfire, these events could adversely impact barrier performance. Thus, understanding how an engineered barrier responds to, and ultimately recovers from, such disturbances is important for predicting long-term performance and obtaining public and regulatory acceptance of barrier technology.

Perhaps the biggest unknown is the effect of wild fire on the evapotranspirative soil layer and ultimately the function on these engineered ecosystems. Research in rangeland and forest ecosystems show that the effects of fire can be quite complex. These range from the reduction, or even elimination, of above-ground biomass, to changes in soil physical and chemical properties, and alteration to microbial mediated processes [1,2]. Wildfire can directly or indirectly alter soil aggregate stability, water repellency, surface runoff response, mineralogy, pH, and nutrient availability as well as fundamental ecological processes such as biomass productivity, vegetation re-sprouting, plant species recruitment, microbial composition, and animal habitat. The damage sustained by plants has been shown to be proportional to the intensity and duration of the fire and the long-term effect is a change in the floristic composition of plant communities. A more immediate effect is the destruction of surface litter and vegetation, leading to a reduction in the protection offered to the soil from raindrop impact and increased runoff [3,4]. Runoff is also enhanced by fire-induced water repellency in the near surface owing to the coating of soil aggregates with hydrophobic organic compounds [5]. Increased runoff is often accompanied by loss of soil from the evapotranspirative soil layer, a reduction in available soil nutrients, and a decrease in water holding capacity.

Owing to the strong coupling between soil properties and ecological processes, fire-induced alterations are site-specific and cannot be easily extrapolated to other ecosystems. However, in engineered ecosystems where nutrients may be already limiting, soil and nutrient loss could inhibit processes necessary for successful barrier performance and recovery from fire. The main objectives of this study were to document fire effects on: (i) soil hydrophysical and geochemical properties, and (ii) ecological processes controlling barrier performance and function as a recovering ecosystem. It is hypothesized that the interplay between fire-induced changes in hydrophysical and geochemical properties and post-fire plant dynamics can affect nutrient availability and soil water balance. To this end, a controlled burn was conducted on one half of the surface of the prototype Hanford barrier in September 2008. The effects of the fire were monitored over the last year and this paper provides a summary of the results to date.

MATERIALS AND METHODS

Physical Setting

The prototype barrier is in 200 East central plateau of the Hanford Site, which is located in semiarid south central Washington State. The long-term average (LTA) annual precipitation from 1946 to the present is 6.85 in (174 mm) with almost half occurring in the winter (November through February). Temperature ranges from as low as 10 °F (-12 °C) in the winter to as high as 115 °F (46 °C) 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). The thick vadose zone on the central plateau (> 300 ft [100 m]) is comprised mostly of coarse glaciofluvial sediments ranging from loamy sand to sandy loam. The relatively deep vadose zone and the difference between AET and PET make this site ideal for use of engineered barriers for waste isolation.

The prototype barrier consists of a 2-m thick silt-loam layer overlying other, coarser materials including sand, gravel, and basalt riprap with each layer serving a distinct purpose [6]. The top 1 m of silt loam contains 15% by weight of pea gravel to minimize wind erosion. The entire silt-loam layer is a medium for plant growth and therefore forms the evapotranspiration layer. The design water storage capacity is 600 mm, which is more than three times the LTA precipitation for the site. Additional layers below the silt-loam serve several functions including the establishment of a capillary break and a biointrusion layer [6,7].

Site Vegetation

Prior to construction of the barrier, the native vegetation at the site was a mix of *Artemisia tridentata* (sagebrush), *Ericameria nauseosa* (gray rabbitbrush), and *Poa secunda* (Sandberg's bluegrass). The silt loam used to construct the barrier was mined at the nearby McGee Ranch where the vegetation is mostly shrubs (22%), with *A. tridentata* being dominant, and grass (23%) with *Poa secunda* accounting for 15.4%. Following construction of the barrier, the surface was vegetated with a mixture of shrubs (*A. tridentata* and *E. nauseosa*) and grasses including *Agropyron dasystacyum* (thickspike wheatgrass), *Hesperostipa comata* (needle and thread grass), *Elymus elymoides* (squirreltail), *Elymus wawawaiensis* (Snake River wheatgrass), and *Poa secunda* (Sandberg's bluegrass). Knowledge of the composition of the plant community is an important aspect of this study as fire can affect the floristic composition and the rate of re-establishment of vegetation that will, in part, be controlled by the existing seedbank.

Performance Monitoring

The barrier is instrumented for monitoring components of the water balance including precipitation, runoff, water storage, and percolation out of the root zone. Water storage is monitored using a neutron hydroprobe and vertically installed shorting-diode time domain reflectometry (TDR) probes. 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 where water is collected by gravity flow and the hydrograph recorded automatically using tipping buckets and pressure transducers [1,2]. Monitoring of deep percolation is facilitated by a 6.5 m × 6.5 m pan lysimeter installed under the northeast section of the asphalt layer [1,2]. Horizontal access tubes facilitate monitoring of water content at the capillary break (1.95 m deep) and beneath the asphalt pad by neutron hydroprobe. Barrier and sideslope stability is monitored using elevation measurements whereas erosion is monitored using erosion pins and any sediment collected from the runoff plot.

Simulated Fire

The simulated fire was limited to the north half of the barrier, which was divided into nine 12 × 12 m plots. Two fuel loads were used in the study, 4.7 and 5.71 tons/acre (10.5 and 12.8 tonnes/ha). The heavier fuel load was on the west and the lighter fuel load on the east side of the barrier surface. A flame height rod was installed in the center of each plot for visual observation of the flame height during the fire and for monitoring temperature. For temperature measurements, type K thermocouples connected to a HOBO® datalogger, were installed 1.5 cm below the soil surface, at the surface (0 cm) and elevations of 1, 10, 30, 100, and 200 cm. Measurements started 3 hrs prior to the fire and continued for some 9 hrs after the fire. Water balance monitoring during and after the fire made use of instruments. Near surface sensors, instrument boxes, and solar panels were covered with fiberglass insulation, aluminum fire blankets for protection [8].

Characterization of Soil Properties

Soil physical and chemical properties were measured before the fire and at one week, 6 months, and 1 year after the fire. The field-saturated hydraulic conductivity, K_{fs}, was measured at nine different locations on each 12 m × 12 m plot using a Guelph permeameter [9]. On an engineered barrier, water movement typically occurs as unsaturated flow, which is controlled by the unsaturated hydraulic conductivity, $K(\psi)$ rather than saturated conditions. To gain insight into any possible effects of the fire infiltration, field measurements of $K(\psi)$ were also measured on each 12 m × 12 m plots using a Guelph tension infiltrometer [10]. Within each 12 m × 12 m plot, four measurements were made, one on each 3 m × 3 m quadrant, to provide representative values before and after the burn. Both methods allowed estimation of the α parameter, which is the inverse of the air entry pressure, P_e, and can be expected to change with changes in soil structure.

Changes in the surface layer composition may be expected as the barrier ages under both deflationary and inflationary influences of soil loss or gain. Such changes could be enhanced in post-fire environment and were therefore investigated by measuring the particle-size distribution of samples collected from 0 cm to 2 cm and 2 cm to 10 on a 3 m × 3 m grid. Soil samples were separated into four grain-size fractions, namely, gravel, sand, silt, and clay, and sub classes (very coarse, coarse, medium, fine, and very fine). The pattern of inflation and deflation was mapped by comparing 1-yr post-burn measurements on 66 erosion pins with pre-burn measurements on the north half of the barrier. An important phenomenon affecting infiltration or water movement in soils after fire is the hydrophobization of originally wettable aggregates by coatings with organic substances of plant origins [11]. To quantify the importance of this phenomenon at the barrier, soil water repellency was measured *in situ* and on pre- and post-burn soil samples using the water-drop penetration time (WDPT) test [12]. Following the initial measurement, three additional measurements were made with the final set being made almost 1 yr after the fire. The effect of fire on soil moisture profiles and water storage was determined from neutron probe measurements of soil water content. Water-content profiles were measured at approximate 1-month intervals following the fire to document changes in storage. Measurements were taken at 0.15-m intervals in the 2-m-thick fine-soil layer.

In addition to hydrophysical properties, geochemical properties were also determined on pre- and post-burn soil samples collected on a similar schedule. Soil samples were analyzed for macronutrients (N,P,K) and micronutrients (Ca, Mg, Na) by Northwest Agricultural Consultants (NWAg) of Kennewick, Washington using procedures described by Gavlak [13]. In addition to soil nutrients, samples were also analyzed to quantify pH, electrical conductivity, soil organic matter, cation exchange capacity, and specific surface area. Selected samples were also analyzed by X-ray diffraction (XRD) methods to determine the effects of fire on mineralogy.

Characterization of Ecological Properties

Plant species composition, including the occurrence of soil cryptograms, was determined for the functional portion of the barrier as well as the north and west sideslopes. The occurrence and density of the dominant shrubs, *A. tridentata* and *E. nauseosa*, were determined by counting the number of shrubs in three age classes (new seedlings, midsized-young, and large-old). In addition, shrub height, greatest canopy diameter, and the diameter at the center of the plant perpendicular to the greatest diameter were measured on 25 shrubs each from the north and south sections of the barrier. Ground cover of grass, shrubs, forbs, litter, soil, and soil cryptogams was also determined for the barrier and side-slopes by visual inspection for each species according to Daubenmire [14]. The LAI was measured on each study plot used to determine cover at the burned and unburned barrier areas and at the two McGee Ranch analog sites. Leaf area index (LAI) was measured with an AccuPAR LP80 Ceptometer at the center of each plot. The LAI values were transformed using the square root because data were Poisson distributed. Pre-dawn xylem pressure potential was measured with a Model 1005 pressure chamber instrument (PMS Instruments) on *A. tridentata*, *S. kali*, and *M. officinalis* on the burned and unburned sections of the barrier. To better understand the effects of fire on post-fire vegetation regeneration, soil seed banks were assessed for the pre- and post-burn conditions using seedling emergence tests. Soil samples were collected from the top 3 cm and stored dry at room temperature until the emergence tests, which were conducted in the climate-controlled greenhouse at Washington State University. Germinated seedlings were identified and counted and the resulting data analyzed separately for each of the most common species. All of these measurements were repeated at two analog sites at the McGee Ranch (the source of silt loam used in the construction of the barrier), one which has not burned in decades and the other which burned about 8 years ago, thereby providing context to the communities on the barrier. After the fire, general assessments of shrub survival, re-sprouting, and recruitment were made at the barrier. In addition, cover was determined at the two McGee Ranch analog sites (old burn and unburned) to provide a comparison for the barrier surface.

RESULTS AND DISCUSSION

Simulated Fire

The fire was ignited at 3:15 PM on September 26, 2008 using drip torches. The fire on top of the barrier was fast moving with flames reaching as high as 9 m (30 ft). The fire lasted approximately 7 minutes by which time all of the imported fuel and most of the natural biomass had been consumed. Flame heights exceeded the 6-m (20-ft) flame-height rods but were estimated using video records with nearby infrastructure being used as a scale (Fig. 1). The time-course of temperature before, during, and after the fire was recorded with HOBO® data loggers. These two temperature time-courses were taken from one tower at the hottest part of the barrier surface. Temperatures ranged from 250 ^{o}C (482 ^{o}F) at 1.5 cm (0.6 in.) below the surface to over 700 ^{o}C (1292 ^{o}F) at 1 m (3.3 ft) above the surface. Air temperature increased much higher than the soil temperature, which can be expected. The soil thermal conductivity is strongly dependent on moisture with dry soils being very poor thermal conductors. This coupled with the absence of significant subsurface fuel would have limited the depth of penetration of elevated temperatures. The effect of the fire on soil temperature persisted for about 2 hours. Fire intensity was verified by soil and air temperature measurements. The relative scorch intensity was greatest on the north to northwest and west sides of the barrier while the lowest values were found along the northeast corner and southeast corners. This pattern is similar to the fuel load and air temperature patterns. After the burn, the surface was examined to identify any mosaic patterns that might be indicative of variable fire severity. Some of the vegetation, particularly near the edges of the barrier was not initially consumed but were later ignited by the fire crew. The lower burn efficiency around the edges may be related to the size and moisture content of the biomass. Plants around the edges of the barrier were typically bigger, perhaps because of a larger amount of available moisture that accumulates near the edge.

Fig. 1. Painted Fire Pole in Foreground Showing Thermocouple Mounted Perpendicular to the Pole at a Height of 2 m.

Fire Effects on Soil Properties

Hydraulic Properties

The one-head and two-head K_{fs} measurements made with the Guelph permeameter before the fire were remarkably similar given the variability typically found in K_{fs} measurements. Nonetheless, these data provide a good reference point for quantifying the effects of fire. A comparison of pre- and post-burn (1 wk, and 1 yr) measurements of K_{fs} measured shows a significant decrease from pre-burn values (Fig. 2). However, after 1 year, K_{fs} had returned to pre-burn values at three out of eight measurement locations. Plots 1, 3, and 7 showed essentially the same K_{fs} values as before the fire, whereas reduced K_{fs} values persisted on Plots 2, 4, 5, 6, and 8. Estimates of the K_{fs} derived from the tension infiltrometer showed a mean of 1.33×10^{-3} cm/s 3.77 (ft/day) with a standard error of 0.009. This value is roughly one order of magnitude larger than the K_{fs} measured in the laboratory on repacked silt-loam samples prior to barrier construction. A reduction in K_{fs} is indicative of a reduction in the volume fraction of large pores or the overall porosity. Such a change is consistent with the loss of soil structure that typically results from wildfire. During the first week, the post-fire estimates of α also decreased from pre-fire conditions. The mean pre-burn α was 0.085 cm^{-1} (0.216 $in.^{-1}$), which is equivalent to a P_e of about 12 cm (4.7 in.).

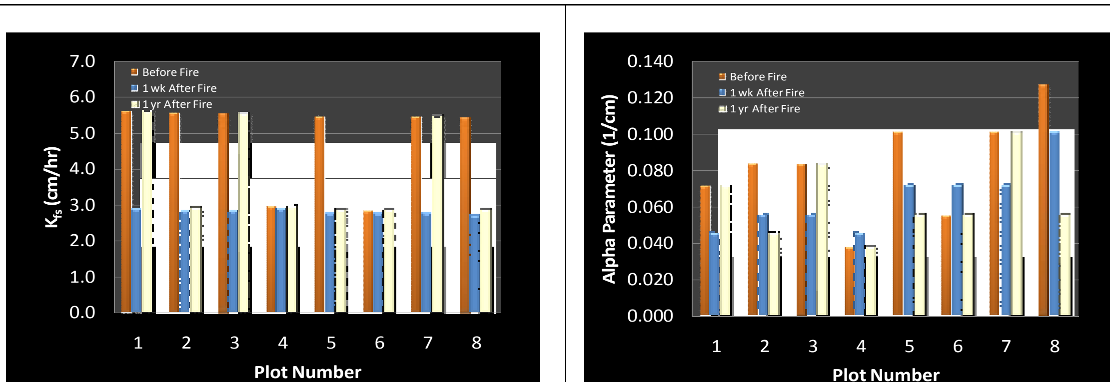

Fig. 2. Comparison of *In-Situ* Pre-Burn and Post-Burn Field Hydraulic Properties, (a) Saturated Hydraulic Conductivity, K_{fs}, and (b) α parameter, the inverse of air entry pressure, P_e.

This value is somewhat small for a silt loam but is consistent with a gravel amended field soil with some structure. The inverse, α^{-1}, is a measure of the air entry pressure, P_e, and a decrease in α is therefore equivalent to an increase in P_e. This can be expected with a decrease in mean pore size or an increase in fines content. The only reasonable explanation for such an increase could be pore plugging due to an increase in ash in the near-surface layers. Estimates of α derived from tension infiltrometer measurements 1 yr after the fire also show that only three out of eight plots had returned to pre-burn values (Plots 1, 3, and 7), whereas five showed essentially the same α as before the fire. Both K_{fs} and α are strongly influenced by pore-size distribution and therefore soil structure. It is clear that for the Warden silt loam used at the barrier, 1 yr is too soon to see a regeneration of the structure that may have been destroyed by the fire. This can be expected as the regeneration of structure will depend on the ground cover and organic matter derived from plant biomass which is still mostly absent. The specific surface area, which controls sorption and the hyper-dry region of the moisture retention function, was also measured. The mean value for the surface soil, sieved to pass a 2-mm (0.08-in.) sieve, was 9.92 m^2/g. This value compares well with independent measurements that range from 8 to 11 m^2/g and remained unchanged after the fire.

Surface Layer Composition and Inflation/Deflation

Measurements with erosion pins also show evidence of inflation and deflation. The greatest loss of soil was 13.5 mm, and the greatest accumulation of soil was 18.5 mm. The greatest deflationary losses of soil occurred on the northwest through the center of the burned area. The greatest inflationary accumulation of soil occurred in the east side of the surface. These changes may be due to localized redistribution of soil from the burned area. In spite of these short-term changes, particle size analyses showed a significant increase in the near-surface gravel content over the last 15 years, which is indicative of deflation in the surface. During the 3-yr of treatability test conducted from 1994-1997, very little erosion was observed. Thus, the increase in gravel in the near surface could be due partly to freeze-thaw processes. The difference between the two sections of the barrier was attributed to deflation due to the simulated 1,000-yr return precipitation events on the north. Long-term freeze-thaw cycles, when coupled with the development of root biomass, could have an impact on the soil bulk density in the near surface. The mean pre-burn dry bulk density on the north section was 1.46 ± 0.054 g/cm^3 whereas the mean post-burn density was 1.442 ± 0.07 g/cm^3, not a significant difference. Some observed changes were largest near sagebrush stumps, suggesting a relationship between with the location of large ash accumulations on the surface. Nonetheless, the short-term decrease in dry bulk density is not statistically significant.

Soil Hydrophobicity

Pre-burn *in-situ* and laboratory water repellency measurements resulted in water-drop penetration times all less than 5 seconds, an indication of fully wettable soils. Immediately after the burn and for 2 months after, field and laboratory measurements showed a significant decrease in wettability. In general, water repellant conditions in unburned areas were found in the leaf litter and at the surface immediately beneath shrubs, before the fire. After the fire, water repellant areas were typically found parallel to the surface but at deeper depths. Water drops penetrated immediately into wettable soils, which were typically bare soil areas (no evidence of plants) and ash-free zones, i.e., free of organic matter before the fire (Fig. 3). However, water-drop penetration tests near shrubs suggested the presence of water-repellant soils with repellency ranging from slightly water repellant to strongly water repellant.

Results indicated some general relationships between soil temperature resulting from wild fire and water repellency: 1) essentially no change in water repellency when soil temperatures were less than 200 ^oC, 2) strong water repellency when soil temperatures were between 200 and 250 ^oC, and (3) absence of water repellency when soil temperatures between 250 and 400 ^oC were recorded. These ranges are consistent with those reported by Debano [15]. Measurements taken over time showed that the intense snowfall in the winter of 2008 resulted in a loss of water repellency by early January 2009, and repellency remained relatively low throughout the winter.

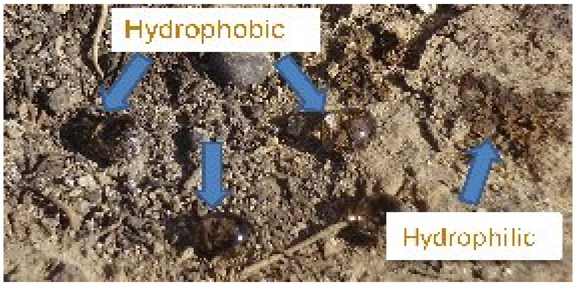

Fig. 3. Photograph of Burned Surface During Water Drop Penetration Test.

Measurements made 1 year later when the soil surface was quite dry still showed evidence of reduced wettability. Only 16% of samples showed signs of decreased wettability after 1 yr. Under these conditions, water repellency appears to be reversible; disappearing when the soil is wet and returning after the soil dries out. For fires occurring in the late summer, elevated water repellency may persist for at least 1 yr under Hanford conditions. Published reports suggest that the time to dissipate can range from less than 1 yr (16) to over 6 yr (17). These observations are of significance to the runoff response of the barrier.

Fire Effects on Soil Water Storage

Water balance is the most comprehensive approach for assessing the field-scale hydrologic performance of an engineered barrier. Thus, observing differences in the water-balance components between the burned and unburned sections should provide insight into the effects of the fire. Robichaud [18] suggested that under fire-induced water-repellent conditions, runoff rates should quickly peak and then begin declining as the hydrophobic substances of the soil are broken down, thus increasing infiltration over time. Before the fire, runoff had been recorded at the barrier on only two occasions, once when the surface was bare, and once after a rapid snowmelt event on frozen surface soil. In the winter of 1997, Chinook winds on frozen surface soils resulted in 36.3 mm of surface runoff with no sediment loss. In January 2009, following the fire, a total of 1.6 L of runoff was recorded. This is equivalent to 0.016 mm, quite small compared to previous events but the first observed in over 15 years. It can be attributed directly to the effects of the fire.

A comparison of the soil water profiles measured on the burned (north) and unburned (south) sections over the last year also show significant differences that can be directly attributed to the fire. These differences are best interpreted in terms of soil water storage, W (Fig. 4). In September 2008, just before the fire, the soil water storage was mostly depleted, and the north and south sides showed no differences in water-content distributions. By January 2009, after a relatively wet winter, a difference in the water-content profiles could be seen between the north and south sections with the south section being considerably wetter in the top 0.7 m and with the north section showing slightly wetter conditions at depth (0.8 to 1.6 m). With both sides receiving the same amount of precipitation, the difference in water-content distribution is due to changes induced by the fire, although the discrepancy is somewhat counter intuitive. The lower near-surface water content can be attributed to increased evaporation from the bare surface whereas the developing moisture front at depth is due to redistribution of water that moved beyond the evaporative depth. The wetting front developing at depth is more obvious in the March 2009 profile. After the start of spring, the depletion in moisture content (owing to plant uptake) increased, and there was a sharp reduction of moisture in the 0 to 0.8 m depth on the south side, whereas the water content at depth continued to increase. The rapid decrease in the top 0.8 m is likely due to uptake by evergreen *A. tridentata* and sparse shallow rooted active bunchgrasses. By June, the profiles had reversed with the burned north section being considerably wetter than the south unburned section with the leading edge of the wetting front persisting at depth. By July, the difference between the burned and unburned sections was much smaller, although the burned section was still wetter.

Perhaps the most striking observation is that despite the removal of plants from the north section, the soil water content was depleted to an amount almost identical to the unburned section. Owing to the relatively low ground cover on the recovering burnt section and the relatively small plants, it is unlikely that this much water was removed

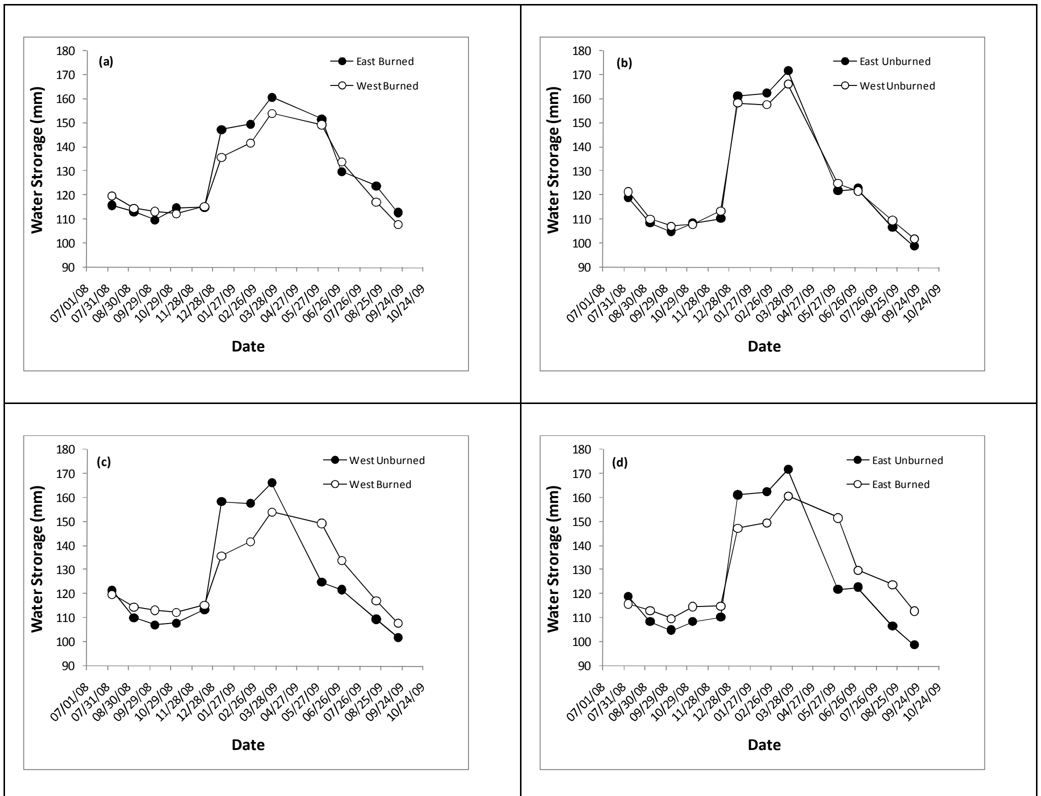

Fig. 4. Post-fire Average Water Storage at the Barrier, (a) North Plots, (b) South Plots, (c) Northwest and Southwest Plots, and (d) Northeast and Southeast Plots.

by transpiration. Thus, evaporation may have been the dominant mechanism. If due entirely to evaporation, the evaporative depth appears to extend much deeper than the top few centimeters that is typically assumed in uncoupled models for predicting water-balance processes. An alternative explanation is higher than expected transpiration on the burned area. While there was relatively little leaf area in the burned area compared with the unburned area, it is possible that root zones were larger and that transpiration rates are relatively high given the strong vapor potential gradient. This would result in a much higher draw-down than on a truly bare soil.

Fire Effects on Soil Nutrients

To assess the effects of fire on the soil chemical system, a number of geochemical properties were measured pre- and post-burn. The results are summarized in Table **1**. Soil pH is known to control the availability of most nutrients, and this is important in nutrient-limiting environments, like engineered ecosystems, where fertilizer is typically not applied. Within the first week of the fire, mean pH increased significantly but subsequently decreased over time. One year after the fire, pH has declined from the immediate post-burn value but remained significantly different from pre-burn conditions. Increases in pH can be attributed to ash accretion [19,20]. The release of minerals as oxides or carbonates is usually an alkaline reaction [21,15]. An increase in pH typically increases the cycling of various elements critical for plant growth. Although pH does not directly control N availability, it does affect soil microbial activity which can affect N availability. Acidic conditions (low pH) limits microbial activity and slows down N mineralization and nitrification whereas high pH can increases N loss by volatilization. The availability of P is strongly influenced by soil pH, reaching a maximum between pH values of 5.5 and 7.5. Basic soil conditions (pH > 7.5) result in an excess of Ca in the soil solution, which can also precipitate with phosphorus, rendering it unavailable.

Table 1. Effect of Fire on Soil Nutrient Status.

Variable	Sampling	Mean	Variance	t_{stat}	P(T≤t) Two-Tail	t_{crit} Two-Tail
pH	Pre-burn	8.036	0.046			
	1 week	8.978	0.147	-12.520	1.74E-14	2.03
	1 year	7.572	0.021	12.925	6.94E-15	2.03
Organic Matter (%)	Pre-burn	0.916	0.053			
	1 week	1.256	0.105	-5.449	4.11E-06	2.03
	1 year	1.374	0.221	-5.622	2.43E-06	2.03
CEC (meq/100 g)	Pre-burn	10.323	0.0023			
	1 week	10.4	0.291	-0.3979	0.7025	2.36
	1 year	9.761	0.387	1.692	1.29E-01	2.31
EC (mmho/cm)	Pre-burn	0.189	0.001			
	1 week	0.493	0.012	-15.905	1.37E-17	2.03
	1 year	0.261	0.005	-6.177	4.52E-07	2.03
Ammonium-N (mg/kg)	Pre-burn	4.050	9.693			
	1 week	15.511	20.559	-12.477	1.93E-14	2.03
	1 year	10.472	24.393	-7.358	1.32E-08	2.03
Nitrate-N (mg/kg)	Pre-burn	3.622	3.461			
	1 week	5.206	2.821	-3.464	0.001422	2.03
	1 year	16.719	71.939	-9.355	4.71E-11	2.03
P-Bicarbonate (meq/100 g)	Pre-burn	11.389	17.787			
	1 week	26.028	49.056	-9.844	1.28E-11	2.03
	1 year	32.528	108.542	-11.747	1.07E-13	2.03
K-Bicarbonate (meq/100g)	Pre-burn	239.750	4276.250			
	1 week	380.472	12136.599	-7.589	6.75E-09	2.03
	1 year	326.611	8974.587	-6.858	5.83E-08	2.03
Calcium	Pre-burn	17.508	0.646			
	1 week	17.692	0.645	-0.935	0.356426	2.03
	1 year	16.253	0.787	7.448	1.02E-08	2.03
Magnesium	Pre-burn	1.409	0.027			
	1 week	2.686	9.328	-2.479	0.018127	2.03
	1 year	1.672	0.037	-6.275	3.36E-07	2.03
Sodium	Pre-burn	0.054	0.001			
	1 week	0.095	0.015	-1.953	0.058824	2.03
	1 year	0.081	0.001	-4.620	5.03E-05	2.03

The pre-burn organic matter (OM) content measured by the Walkley-Black method was 0.916% and increased to 1.256% and 1.374% after one week and one year, respectively. After one year, OM appears to have increased by about 50% from pre-burn conditions. The OM content is often used as an indication of soil productivity and can be used to estimate the N release. The amount of available N released to the plant is about 28 to 56 kg of actual N per hectare per year for each percent of OM and depends on a number of factors including soil water content, temperature, and length of growing season. The pre-burn OM is equivalent to 26 to 51 kg of nitrogen per hectare per year compared to 35 to 70 kg of N per hectare per year after one week and 38 to 77 kg of N per hectare per year after 1 year. These results are somewhat counter intuitive as heating the soil to temperatures between 220 and 460 ^{o}C is known to destroy organic matter to depths of up to 80 mm. There is no physical explanation of the apparent increase in OM by the Walkley-Black method. However, OM determined by loss on ignition showed an 8% decrease over the same period. Decrease in OM can alter the CEC, however, as shown in Table 1, CEC did not show any statistically significant changes between pre- and post-burn conditions.

Electrical conductivity measured on 1:1 extracts, $EC_{1:1}$, showed a significant increase from 0.189 mmho/cm to 0.493 mmho/cm within the first week but had decreased to 0.261 mmho/cm one year later. Electrical conductivity of the soil is a measure of the amount of soluble salts present and hence the salinity. The tendency of fire to volatilize nutrients, increase soil concentrations of mineral elements, and reduce available moisture is consistent with the observed increase in $EC_{1:1}$. In fact, soil elemental analyses indicate that concentrations of major nutrients increased following the fire. While this could potentially result in a short-term increase in nutrient availability, it also results in an increase in salinity, which could have detrimental effects on establishment of vegetation. $EC_{1:1}$ alone, however, is insufficient to assess the effects of salinity on plant growth because the salt concentration at the root surface can be much greater than in the bulk soil. The saturated paste value, EC_e, is a better measure and can be estimated from $EC_{1:1}$ as $EC_e = 2.2\ EC_{1:1}$. The estimated EC_e before the fire was 0.416 dS/m. The estimated EC_e one week after the fire was 1.085 dS/m, compared to 0.574 dS/m one year after the fire. Soils with EC_e values in the range 0 to 2 dS/m are considered non-saline and are not expected to have any effect on plant growth.

The responses of individual nutrients to fire are different. Furthermore, each nutrient has an inherent temperature threshold where volatilization occurs [15,22]. These thresholds can be divided into three general nutrient categories: sensitive, moderately sensitive, and relatively insensitive. Nitrogen [23] and S [24] are considered sensitive because they have thresholds as low as 200 to 375°C, respectively. Potassium (K) and P are moderately sensitive, having threshold temperatures of 774 °C [22]. Magnesium (Mg), Ca, and Mn are relatively insensitive, with high threshold temperatures of 1,107 °C, 1,484 °C, and 1,962 °C, respectively. Because the threshold temperatures of N, P, and K are lower than the flaming temperatures of woody fuels (100 °C) and, except for P, lower than glowing combustion temperatures (650 °C), these nutrients are readily volatilized from soil organic matter during combustion. Thus, significant changes in the soil concentration of N, P, and K can be expected.

On a plot-by-plot basis, the responses of N to the fire varied with different fuel load and soil temperature. Post-burn NH_4-N concentration increased from 4.050 mg/kg to 15.511 mg/kg, a 282% increase after one week but subsequently decreased to 10.47 mg/kg after one year. Concentrations of NH_4-N can increase, decrease, or remain unchanged, depending on fire severity and duration. Increases in NH_4-N immediately following the fire appear to be related to the soil temperature reached. DeBano [5] suggested that most of the soil N is volatilized by high-severity fires, particularly on or near the surface with only small amounts being transferred downward through the soil. Conversely, large amounts of NH_4-N are typically found in ash and underlying soil after low-severity fires. Heat can intensify physiochemical processes including the decomposition of nitrogen-containing organic matter and the release of ammonia from soil minerals [25]. Ammonia loss peaks at 250 to 300^{o}C as a result of volatilization, which explains why NH_4-N increased while organic N decreased [22]. Nonetheless, increases in the soil NH_4^+ pool is appears to have been only temporary and has shown a gradual decrease since reaching 10.47 mg/kg one year after the fire. This is consistent with observations of Wan [26] who reported a gradual decrease to pre-fire levels after about 1 year. The NO_3-N also showed a significant increase following the fire (Table 1). The mean concentration of NO_3-N after one week increased from 3.6 mg/kg to 5.206 mg/kg and to 16.72 mg/kg after one year, an increase of over 300%. Comparatively small increases (24%) have been reported in the soil NO_3−N pool immediately after a fire with a continued increase over time reaching a maximum of approximately three times the pre-fire level within 0.5 to 1 years after fire, followed by a decline [26]. Studies of prescribed fires show an increase in nitrogen for 2 or 3 months following the fire [27].

The mean pre-burn P concentration was 11.389 meq/100 g compared to a post-burn value of 26.03 meq/100 g at one week and 32.5 meq/100 g at one year after the fire. This represents a 124% increase in P after one week and a 185%

increase after one year. Phosphorus is known to respond differently to elevated temperatures than N. As much as 60% of the total P is typically lost by non-particulate transfer when organic matter is totally combusted [22]. As a result, relatively large amounts of highly available P can be found in the ash and on the soil surface immediately following fire. However, this P can be quickly immobilized in insoluble compounds especially if soil is rich in Ca. While there have been numerous reports on the effects of fire on the availability of N and P, comparatively few studies discuss other nutrients like K, Ca, Na, and Mg. Table 1 shows that K increased by 58.6% immediately after the fire but subsequently declined to 326.6 meq/100 or 36% above pre-burn levels. Soil concentration of Mg increased by 91% after one week but had returned to pre-burn levels after 1 year. In contrast, Ca and Na remained statistically unchanged. These results are therefore consistent with published reports, which suggest that all of these cations may increase after fire [28,22]. Increases in soluble K in the litter and A horizon, or topsoil, have been reported when temperatures remain below 200^{o}C whereas Ca, Fe, and Mn have been reported to decrease [29]. However, they also found that if the plot burned in consecutive years, then K, Cu, Fe, and Zn availability increased.

Fire Effects on Ecological Properties

Ground Cover

Fig. 5 shows an aerial photograph of barrier on September 30, 2009, one year after the controlled burn. One year after the fire, as can be expected, bare ground is now higher in the burned section (76.6 ± 1.09 %) compared to the unburned section (53.8 ± 2.06%) of the barrier. The burned (north) section now has the same ground cover of grasses (3.51 ± 0.42 %) as the unburned (south) section (1.86 ± 0.18%). However, shrub cover in the burned section (1.46 ± 0.16%) is much lower than in the unburned section (30.3 ± 1.13%). Plant litter (dead leaves, twigs etc) is also now lower in the burned section (7.95 ± 0.52 %) compared to the unburned section (45.3 ± 1.7 %). Ground cover values at the prototype barrier are in sharp contrast to those observed at the two analogue sites at the McGee Ranch. Grass cover on the barrier is quite low when compared to the McGee Ranch old burn (58.9 ± 4.88 %) and unburned (23.1± 1.82 %) sites. Shrub cover in the McGee Ranch unburned area is lower (22 ± 2.57 %) than that in the unburned area on the barrier (30.3 ± 1.13 %). Forb cover is similar in the two burned areas, 24.7 ± 0.97 % at the barrier and 19.8± 2.19 % at the McGee Ranch old burn, than in the unburned barrier (0.4 ± 0.1 %) and unburned McGee Ranch (8.1± 1.4 %). There was no soil cryptogam on the burned half of the barrier, but low cover percentages were observed at the McGee Ranch burned area (6.79 ± 1.98 %) compared to those at the unburned barrier (28.3 ± 1.63 %) and unburned McGee Ranch (42.6 ± 3.57 %).

Fig. 5. South Facing Aerial View of the Barrier on September 30, 2009 Showing the Burnt North and Unburned South Section 1 yr after the Fire.

Table 2 identifies the plant species on the burned and unburned treatments of the barrier and at the two McGee Ranch analog sites. Fig. 6 compares the total number of species on the barrier surface from 1995 through 2009. Species richness on the barrier has dropped from 35 in 1997 to 10 in 2008 just before the fire. Nearly 1 year after the fire, species richness increased to 15 in the unburned half of the surface and increased markedly to 24 species on the burned half of the surface. Species richness at the two analog sites is essentially the same as on the unburned half of the barrier. Annual and biennial species are 32% of the flora in the long-term undisturbed community at the McGee Ranch, 44% in the McGee Ranch old burn, 53% in the unburned barrier surface, and increasing to 58% on the burned half of the barrier. The dominance of *A. tridentata* on the unburned half of the barrier surface may contribute to continued

Table 2. Plant Species Observed in 2009 on the Burned and Unburned Sections of the Barrier Plus at two McGee Ranch Analog Sites.

Family	Species	Barrier Burn	Barrier Unburned	McGee Old Burn	McGee Unburned
Asteraceae	*Achillea millifolium*	X			
	Artemisia tridentata	X	X	X	X
	Balsamorhiza careyana			X	
	Centaurea diffusa	X	X	X	
	Chrysothamnus viscidiflorus	X	X		
	Crepis atribarba				X
	Ericameria nauseosa	X	X	X	
	Erigeron filifolius				X
	Erigeron piperianus				X
	Erigeron poliospermus				X
	Helianthus cusickii			X	X
	Lactuca serriola	X			
	Machaeranthera canescens	X	X	X	X
	Stephanomeria paniculata	X			
	Tragopogon dubius	X		X	
Boraginaceae	*Amsinckia lycopsoides*	X	X		
Brassicaceae	*Descurainia pinnata*	X		X	X
	Sisymbrium altissimum	X	X	X	
Chenopodiaceae	*Chenopodium leptophyllum*	X			
	Grayia spinosa				X
	Salsola kali	X	X	X	X
Fabaceae	*Astragalus caricinus*	X			
	Melilotus officinalis	X			
Geraniaceae	*Erodium cicutarium*	X	X		
Malvaceae	*Sphaeralcea munroana*			X	X
Family	Species	Barrier Burn	Barrier Unburned	McGee Old Burn	McGee Unburned
Poaceae	*Achnatherum hymenoides*			X	X
	Bromus tectorum	X	X	X	X
	Elymus elymoides			X	X
	Elymus wawawaiensis	X	X		
	Poa ampla	X	X		
	Poa bulbosa	X	X		
	Poa secunda	X	X	X	X
	Vulpia microstachys	X	X		X
Polemoniaceae	*Phlox longifolia*			X	
Verbenaceae	*Verbena bracteata*	X			
	Total Number of Species Present	24	15	16	16

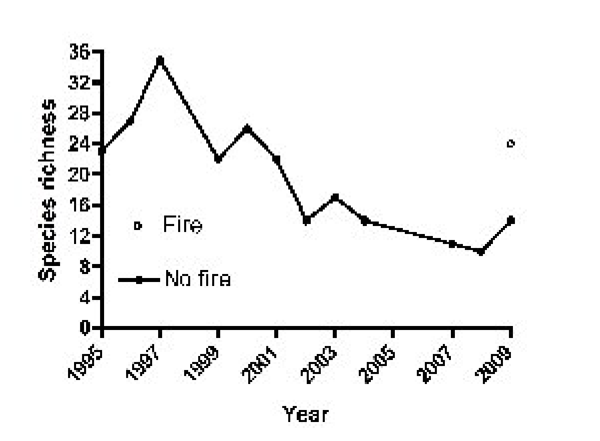

Fig. 6. Temporal Variation in the Number of Species on the Prototype Hanford Barrier from Inception Through September 2009, 1 Year After the Fire.

reductions in species richness on the surface. Similar species richness was found at the unburned McGee Ranch analog site that is also dominated by *A. tridentata*. This is in contrast to the similar richness at the burned McGee Ranch analog site, even though *A. tridentata* has very low cover. Factors other than dominance by *A. tridentata* are determinants of species richness. It is likely that the increase in species richness after fire is a short-lived consequence of fire given that the old burn at McGee Ranch had essentially the same species richness.

Shrub Density

Post-burn shrub density varied among the four study sites. After one year, the density (plants per m^2) of *A. tridentata* was very low on the burned section of the barrier (0.0146 ± 0.0054) and essentially equivalent to that at the McGee Ranch old burn site (0.0147 ± 0.0031). The density was significantly higher on the unburned barrier (0.77 ± 0.0121) than at the McGee Ranch unburned analog site (0.437 ± 0.0331). *E. nauseosa* established in significant, but low numbers (0.00386 ± 0.00202) after the fire on the barrier surface. This and other shrubs were present only in low numbers.

Seed Bank Assessment

After the burn on the barrier surface, a significant number of shrubs germinated from the seed bank and/or from seed that arrived at the site. However, there was no difference in the number of species emerging from the seed bank before and after the fire. The most interesting observation is the emergence of *A. tridentata* from the seed bank after the fire, which suggests that this dominant shrub will return after fire. This observation is in contrast to the general belief that *A. tridentata* does not recover after a fire. There was no evidence of re-sprouting after the fire. There is evidence of *A. tridentata* in the seed bank, so it is likely that those found on the burned barrier surface are from the seed bank. *A. tridentata* seed is not wind-borne. In contrast, while 88% of the new shrubs on the burned barrier surface were *E. nauseosa,* none were found in the seed bank. If they were in the seed bank, they may not have had the appropriate conditions to germinate. It is possible that these new recruits arrived from nearby plants that released wind-borne seed after the fire. While there are few *E. nauseosa* plants in the adjacent unburned barrier surface, there are numerous shrubs on the adjacent side slopes that can be the source of the new recruits on the burned surface. There were no significant differences among the barrier plots before and after the fire and the unburned McGee Ranch site. Both *S. kali* and *S. altissimum* were significantly greater on the old burn McGee Ranch site than at the unburned McGee Ranch site while there were no seedlings observed from any of the barrier samples. Both species were found growing on the barrier surface after the fire, suggesting that viable seed is either in the seed bank, and they did not germinate from the samples in the greenhouse, or the seed arrived on the surface after the fire from surrounding seed sources. Both species are recognized as responding favorably to fire. *Verbena bracteata* seedlings were found in the seed bank of samples before and after the fire. None were found on the side slope or at the two McGee Ranch sites. When emerged seedlings of all species were combined in each experimental unit for the high (n = 17) and low (n = 19) fuel load areas on the barrier surface, there was no significant ($p = 0.86$) effect of fire intensity on seedling density.

Leaf Area Index and Plant Water Status

Post-burn measurements of LAI show that the mean LAI on the unburned half of the barrier (1.13 ± 0.087) was not significantly different from mean LAI in the McGee unburned plant community (0.692 ± 0.129). The mean LAI in the burned half of the barrier (0.254 ± 0.02) was not significantly different from the mean LAI in the McGee old burn plant community (0.103 ± 0.0.031). Values in the two burned areas were significantly lower than those in the two unburned areas. The xylem pressure potential was measured on plants in the burned and unburned conditions.

Measurements were made just before dawn to assess maximal xylem pressure potential. There was no significant ($p = 0.570$) effect of species on xylem pressure potential for early morning readings in the burned condition. These values were then combined to test the effect of location on xylem pressure potential in the burned condition. Location had a significant ($p = 0.0045$) effect on xylem pressure potential. Plants on the west third of the surface had significantly greater xylem pressure (-17.5 ± 0.89 bars, n = 12) than those on the middle and east thirds of the surface (-26.3 ± 2.49 bars, n = 13). This observation suggests that similar variation in the soil water potential may exist on the burned half of the barrier.

Biological Activity and Soil Carbon Dioxide Flux

Soil respiration rates in the burned and unburned conditions were compared when surface soils were dry and when surface soils had been wetted by rain to an average depth of 33.8 ± 1.1 mm. When the upper soil profile was dry, soil respiration rates (μmol CO_2 m^{-2} s^{-1}) were significantly ($p = 0.0205$) greater in the burned treatment (0.134 ± 0.018) than in the unburned treatment (0.074 ± 0.013). After wetting the upper soil profile, there was no significant ($p = 0.3394$) difference between the treatments. Given that observations were taken from the same location in wet and dry conditions, dry rates were subtracted from wet rates and compared between the treatments. These differences were not significantly ($p = 0.1936$) different. Thus, observations in the treatments were combined to compare wet and dry rates. Soil respiration rates were significantly ($p < 0.0001$, n = 12) greater in the wet surface soils (0.834 ± 0.0725) than in the dry surface soils (0.104 ± 0.0137). The higher respiration under dry conditions in the burned area compared with the unburned area is likely a result of the wetter soil profile. The wetter soil profile, as evidenced by plants with higher water potential values, yields more active plants that have higher root-respiration rates. It is likely that soil respiration is primarily root respiration given that the soil surface was very dry, limiting surface microbial activity. When the surface soils were wetted, it is likely that a significant component of the respiration was microbial. Given that soil organic matter increased or decreased depending on the assessment method after the fire, it is possible that there was enough organic carbon in the burned soil to support respiration rates as high as in the unburned soil.

SUMMARY AND CONCLUSIONS

A critical unknown in long-term engineered surface barrier use for waste site remediation is the post-fire hydrologic function where institutional controls are intact, but there are no resources to implement maintenance activities, such as re-planting of vegetation. A study was recently conducted at the Hanford Site to gain insight into the effects of wildfire on the function of an engineered barrier. The north half of the barrier was amended with imported fuel with the west side getting the largest load and the east side getting the lowest fuel load. The barrier was ignited along the perimeter and the surface was completely burnt in about 7 minutes with flame heights exceeding 9 m (30 ft), and temperatures ranging from 250 °C (482 °F) at 1.5 cm (0.6 in.) below the surface to over 700 °C (1292 °F) at 1 m (3.3 ft) above the surface. The relative fire intensity was consistent with the fuel distribution.

One week after the fire, non-destructive and destructive measurements were made to quantify changes in soil hydrophysical and geochemical properties, including nutrient status. Post-fire analysis of soil properties shows significant decreases in wettability, hydraulic conductivity, air-entry pressure, organic matter, and porosity relative to pre-fire conditions, whereas dry bulk density increased. Decreases in hydraulic conductivity and wettability, one week after the fire, are implicated in a surface runoff event that occurred in January 2009, the first runoff event in 13 years. There was a significant increase in macro-nutrients, pH, and electrical conductivity. Measurements repeated after one year show that hydrophobicity has returned to pre-burn levels with only 16% of the samples still showing signs of decreased wettability. Over the same period, hydraulic conductivity and air-entry pressure returned to pre-burn levels at one third of the locations but remained identical to values recorded immediately after the fire at the other two thirds. Soil nutrients, pH, and electrical conductivity remain elevated.

Species composition on the burned surface changed markedly from prior years relative to the unburned surface and two analogue sites. There was an increase in the proportion of annuals and biennials, which is characteristic of burned surfaces that have become dominated by ruderal species. However, it anticipated that native perennial species will come to dominate the burned area again as *A. tridentata* and *E. nauseosa* have started to re-establish. Observations at the old burn analogue site suggests that *A. tridentata* will produce an abundance of seed as long as competition remains low, and there is access to stored water to support the high seed production. Greenhouse seedling emergence tests conducted to assess the seed bank at the barrier and analogues sites show no difference in the number of species emerging from pre- and post-burn soils. However, there were fewer species emerging from the side-slope seed bank whereas more emerged from two analogue sites. Xylem pressure potentials were considerably higher on the burned half of the barrier in September 2009, suggesting that not all the water in the soil profile may be removed before the fall rains begin. Greater soil respiration rates under dry surface conditions in the burned area compared with the unburned area observations support the supposition that plants experiencing wetter soil profiles will show more active root respiration. Continued soil respiration observations may be a good surrogate of root activity as the vegetation recovers.

There were significant differences in the rate of accumulation and loss of soil moisture on the burned and unburned sections. On the burned section, water storage was higher during the fall, increased more slowly with the onset of winter precipitation owing to higher evaporation, and decreased more slowly in the spring owing to lower evapotranspiration. The result was significantly higher water storage on the burned section at the end October 2009, which translates into a lower storage capacity prior to the onset of winter precipitation. Nonetheless, barrier effectiveness has not been compromised as the storage capacity is some 600 mm. The results of this study are contributing to a better understanding of barrier performance after major disturbances in a post-institutional control environment. Such an understanding is needed to enhance stakeholder acceptance regarding the long-term efficacy of engineered barriers.

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