Part 3: Soil Properties, Erosion, and Implications for Rehabilitation and Aquatic Ecosystems

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Introduction

This team was asked to address three questions regarding soil properties, erosion and sedimentation, and how aquatic and terrestrial ecosystems have responded or could respond to various land management options. We have used soil survey maps, burn severity maps, and digital elevation model (DEM) maps as primary map data. We used our own field measurements and observations coupled with previous research and professional judgment in addressing these questions.

Question 1: What was the historic range of variability (pre-1860) in the frequency, extent, and locations of mudflows and other erosion/sedimentation events (related to fire or other processes); how did the frequency, extent, and locations of erosion/sedimentation events in the recent period (1860 to 2002) compare with historic conditions; and how are events in the near future (next approximately 5 years) likely to compare with the historic range of variability?

Question 2: Where were key soil properties altered by the fire (including such things as organic matter content, water repellency, and productivity); and how long are these changes likely to persist?

Question 3: Where are fire-induced changes in soil properties likely to adversely affect recovery of aquatic and terrestrial ecosystems (over the short and long term) if no postfire rehabilitation is attempted; where are soil rehabilitation efforts likely to improve recovery of aquatic and terrestrial ecosystems; and where is soil rehabilitation unlikely to improve recovery of aquatic and terrestrial ecosystems?

Historical Analysis

The degree of soil development and movement of soil materials is dependent upon the climate, parent material, time, vegetation, and the intensity and size of disturbances. Human disturbances of the landscape during the past 100 years has significantly altered biotic factors and disturbance factors. Consequently, soil development and soil movement may have been much different, spatially and temporally, in the recent period (1860 to 2002) than during the thousands of years before humans became a component of the landscape. The imbalance between soil development processes and disturbances that degrade or dampen soil development may potentially have long-term effects on the health and integrity of the landscape.

Wind and water erosion on agricultural and nonagricultural lands removes 4 billion tons of soil annually in the United States (Brown and Wolf 1984). Two thirds of this amount is moved by water and one-third by wind. In forested areas erosion can occur by a wide variety of processes, including soil creep, dry ravel, mass movements including slumps and slides from slope failure, and biogenic transport (for example, animal burrowing or tree throw). In most undisturbed forests erosion rates and sediment yields are typically low (Dunne and Leopold 1978). Unpaved roads, rural and urban development, and forest management activities will usually increase erosion rates, but the net effect on waterways and aquatic habitat is highly variable. Because most forested areas in the Colorado Front Range (and to a degree in the Hayman Fire area as well) have sandy and gravelly soils with high infiltration rates and hence little overland flow, much of the sediment eroded from a site may not make it to the stream. In such cases, an increase in erosion may have relatively little adverse effect on stream channel morphology and aquatic ecosystems. On the other hand, erosion is likely to remove much litter and some of the surface mineral soil layer. Both of these are sources of onsite nutrients and organic matter, in which case loss by erosion will have a direct, adverse effect on site productivity. Drainage from roads and developed areas often flows directly into the stream network, and the increase in runoff and/or sediment can adversely affect downstream resources and aquatic ecosystems.

Pre-1860 – The historic range of variability for pre-1860 disturbance patterns has not been well documented. Potential sources of information for reconstructing landscape patterns and processes are early journals and more formal land survey records. Land survey records were made as early as the mid 1700s for Eastern portions of the United States, but not until the latter 1800s for portions of the Western United States. These land survey records can be examined for evidence of historical disturbance as the surveyors kept detailed journals on forest cover type, local topography, soil conditions, and other landscape features. This information can be used to infer the "presettlement" condition. Alterations to this presettlement condition may then be recorded as lands were resurveyed. The strengths of this technique are that (1) it is often geo-referenced, and (2) in many cases it reveals the presettlement condition and how disturbance (natural and human) had altered the landscape. However, its limitations are that (1) the presettlement reference condition represents a point in time, and (2) it is not able to establish conditions and processes existing prior to that point in time. This method is also limited by the landscape interpretation made by the surveyor (as surveyors changed, so did the interpretation quality). The quality of interpretations is especially important in this case because the information is not quantitative. In this evaluation of the Hayman Fire we did not directly use any information from early journals or land survey records.

However, descriptions and documentation of soil erosion in the vicinity of the Hayman Fire as early as the 1880s do exist, and are discussed in the next section "1860 to 2002." From these sources, we might surmise that, prior to 1860, soil erosion was much less severe than in later periods as activities such as logging, mining, and grazing increased. It is likely that in the past, soil erosion patterns varied temporally and spatially and were correlated to long-term climate and to significant events such as 50, 100, and 500-year storms.

The key controlling processes that contribute to soil erosion and mass movement of soils in the assessment area are the effects of water movement and wind transport of materials. Both of these weathering agents transport sediment and are highly dependent on local climatic variability, local topography, ground cover, and geologic substrate (parent material).

Mass movement of soil material is characterized by the presence of debris/mud flows within an area and is generally considered to be episodic and is likely driven by large storm events. Slope failures resulting in slumps of slides may occur after severe burns on slopes that would otherwise be stabilized by the presence of forest vegetation. One factor involved in postfire slope failure is the increasing buildup of water in the soil in the absence of vegetation, which increases soil weight and downward forces on the slope. After slope failure, the disturbed area is subject to further erosion by rainfall and snowmelt.

Erosion by water has specific mechanisms that tend to degrade the system over large spatial and long temporal scales. For example, the impact of raindrops erodes soil by first detaching the soil and destroying aggregates, making the soil more susceptible to movement. The force of the splash will then initiate overland sheet erosion that combines to form rills. As rills concentrate and erosive power increases, gullies or channels exhibiting downward cutting are formed that are capable of delivering large volumes of sediment-laden water to wetlands and waterways.

The specific mechanisms for wind erosion involve the processes of detachment and transportation. The initial detachment of soil particles from granules or clods results from the lifting power of the wind. Whereas silt-sized particles become airborne and can be transported long distances, medium-sized particles (0.05 to 0.5mm) bounce along the soil surface dislodging other particles as they move.

Morris and Moses (1987) documented soil movement following forest fires for five ponderosa pine forested catchments along the Colorado Front Range. They found that the sediment flux rates following forest fires was elevated by three orders of magnitude in comparison to control catchments of undisturbed forest. They suggested that the two most significant variables controlling sedimentation were (1) the fire-induced formation of a water repellent layer in the soil and (2) the tendency for surface debris to become detachment limited. They concluded that forest fire disturbances might account for a large portion of the long-term sediment yield from Front Range hill slopes. Given the extreme weather events common to the Colorado Front Range, we can hypothesize that the erosion events that are occurring since the Hayman Fire might have occurred prior to settlement, and may be within the range of historic variability.

1860 to 2002 – Several excellent sources document soil erosion in the vicinity of the Hayman Fire and on the Pike National Forest, beginning as early as the 1880s. The Forest Service photographic archives in Pueblo, CO, contain photographs of the Pike National Forest as early as 1920, often commenting on the soil erosion effects shown. A caption on one photo makes reference to natural regeneration after an 1880s fire. Some of the history of the Pike National Forest since its formation in 1907 is detailed on the Forest Service Web page, "...the story behind the Pike National Forest" by Vance and Vance (World Wide Web address fs.fed.us/r2/psicc/pp/history.htm [2003]). It documents some of the disturbance history of the Forest and what the erosional responses to fire, logging, mining, and grazing have been. Even earlier, Jack (1899) reported descriptions of soil erosion in some of the watersheds in what is now the Pike National Forest. He included both maps and photographs of observed erosion. Connaughton (1938) reported "excessive erosion" due to overgrazing by domestic livestock as well as erosion resulting from wildfire. Elliott and Parker (2001) discuss the long-term effects of soil erosion following fire.

The United States Geological Survey (USGS) initiated erosion and deposition studies in the Buffalo Creek watershed immediately following the 1996 Buffalo Creek Fire. They measured hydrological and erosional responses of severely burned hillslopes by monitoring runoff, rill erosion, and interrill erosion, as well as measuring postfire sedimentation (Moody and Martin 2001a). Coupled with other related studies (Martin and Moody 2001a,b; Moody and Martin 2001a,b,c; Moody 2001) these extensive measurements provide an excellent understanding of postfire erosion, deposition, runoff, and fire-induced changes in soil properties and behavior. Some of these studies are especially relevant because they were conducted on the Buffalo Creek Fire, which occurred in the same general geologic terrain as the Hayman Fire. It is not unreasonable to expect some similar postfire behaviors in the two areas.

Figure 6 is a burn severity map of the Hayman Fire area with the topographic map background and five observation points in the northern part of the burn north and west of the town of Deckers and in the Saloon Gulch area. (These same five observation points are plotted on most of the other maps as well). Areas shown as *high severity* burn are of primary concern in this analysis, as related to (1) potential erosion and sedimentation, (2) where key soil properties were altered, and (3) where fire-induced soil changes will adversely affect recovery of aquatic and terrestrial ecosystems.

Figure 7 is a map of soil surface textures in the burn area. It is interesting to note that much of the area in the western part is mapped as weathered or unweathered bedrock and that in the eastern part there is a large extent of soils that are not sandy and/or gravelly; specifically, soils with clay loam surface textures. Many of the conclusions in this report are based on the fact that forest soils in the Front Range are dominantly coarse textured. Most of the clay loams were not in the severely burned areas, and from figure 8, are not as steep in general as soils to the west.

Key soil properties used from the soil map were (1) surface/subsurface texture, (2) mineral soil organic matter content (OM, SOM, or SOC), (3) soil depth to bedrock, (4) presence/absence of bedrock outcrop at the surface, and (5) slope. Slope information is also available in a different format and in greater detail as a DEM. The soil survey maps had limited information on surface litter.

Figure 9 shows the intersection of high SOM (greater than 3 percent of the mineral soil) with high burn severity (shown in orange). The spatial extent of this intersection is similar to the high burn severity extent, an indication that most of the high severity burn area had high SOM, although there were a few areas that did not. We believe that most of this common area had a significant amount of litter on the surface of the mineral soil prior to the burn. Field observations verified nearly total destruction of the litter layer in high severity burn areas, as was expected. In part 1 in this report, the effect of high severity burn on soil is described as the fire consuming all or nearly all organic matter on the soil surface (the terminology "organic matter on the soil surface" refers to what we call "surface litter" in this report), as well as soil organic matter in the upper soil layer, and killing all of nearly all of the plant structures (such as roots and rhizomes) in the upper soil layers, resulting in possible water repellency and slow vegetative recovery.

The areas shown in orange on this map (fig. 9) likely had the most surface litter and SOM in the mineral soil surface layer in the burned area prior to the burn, and likewise had the least after the burn. There has been a considerable loss of nutrients and productivity in these areas, resulting from the fire.

Figure 8 is a three-dimensional rendering of the Hayman Fire DEM, draped with a 15-m resolution Landsat panchromatic image and the high severity burn/high SOM intersection extent (in yellow). In this view of the area from a south-southwest perspective, it appears that some of the high SOM/high severity burn occurred on the steeper slopes, which would be more prone to soil erosion than would more gentle slopes (all other factors being equal). It could prove useful to do additional evaluations of these areas; however, within the scope of this study we were unable to make any field observations in this vicinity.

A slope stability analysis model was developed to identify areas of potential slope failure, slumping, or sliding, which could contribute to mudflows, soil erosion, and sedimentation. Slope stability is dependent on many factors that balance resisting forces and driving forces. The ratio between resisting forces and driving forces, the factor of safety, is useful to quantitatively evaluate a slope's willingness to remain stable (Ritter and others 2002). The factor of safety utilizes soil cohesion, soil weight, soil depth, soil pore pressure, and slope angle in calculating the risk of slope failure. The resisting forces incorporate soil cohesion, soil pore pressure, soil depth, soil weight, and slope angle. Driving forces include soil depth, soil weight, and slope angle. Factor of safety values are centered around 1, with 1 being the slope stability threshold. Values greater than 1 indicate the slope is instable, whereas, values less than 1 indicate the slope is in equilibrium. In the Hayman Fire area the loss of vegetation will result in increased soil moisture content, which increases pore pressure within the soil profile, which decreases the factor of safety.

Figure 10 is the output map from the slope stability model analysis. Only the areas shown in red fall below the critical threshold, and they also correspond to the steepest slopes in the burn area. Conclusions from this analysis are that, given the input parameters we used, slope failure does not appear to be a major concern in the Hayman Fire area. To have more confidence in the model rendering of the "risk areas" in the western part, additional fieldwork would be necessary to validate the input parameters used.

High severity wildfires represent one of the greatest potential threats to site productivity, soil resources, and aquatic ecosystems in the Colorado Front Range. In the Buffalo Creek Fire of May 18, 1996, approximately 7,500 acres were mapped in the BAER report (Bruggink and others 1998) as high intensity burn. In the first few months after the fire, and the following summer, a series of storms impacted the area. These caused a great deal of erosion and sedimentation, with

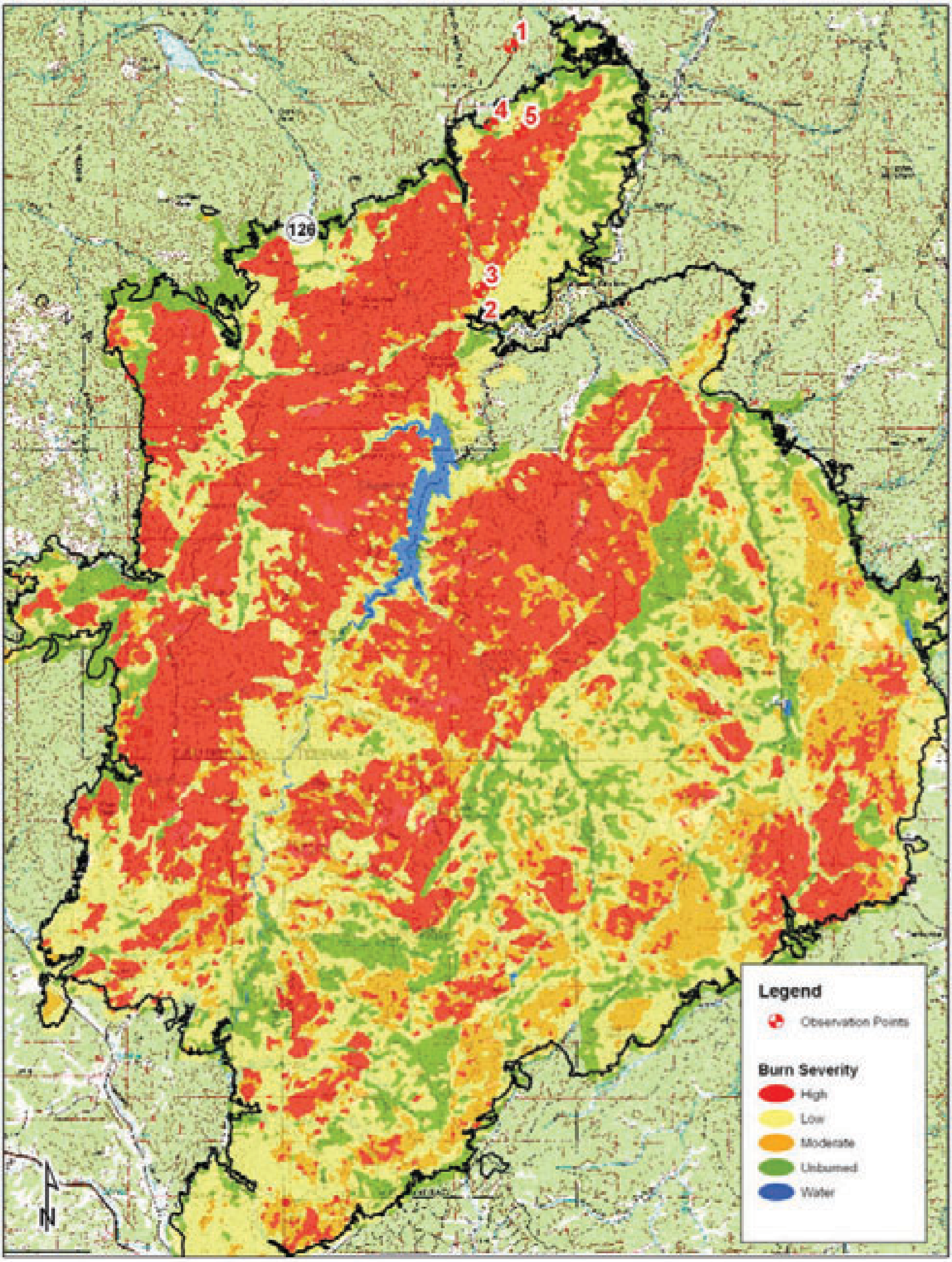

Figure 6—Burn severity map of Hayman Fire.

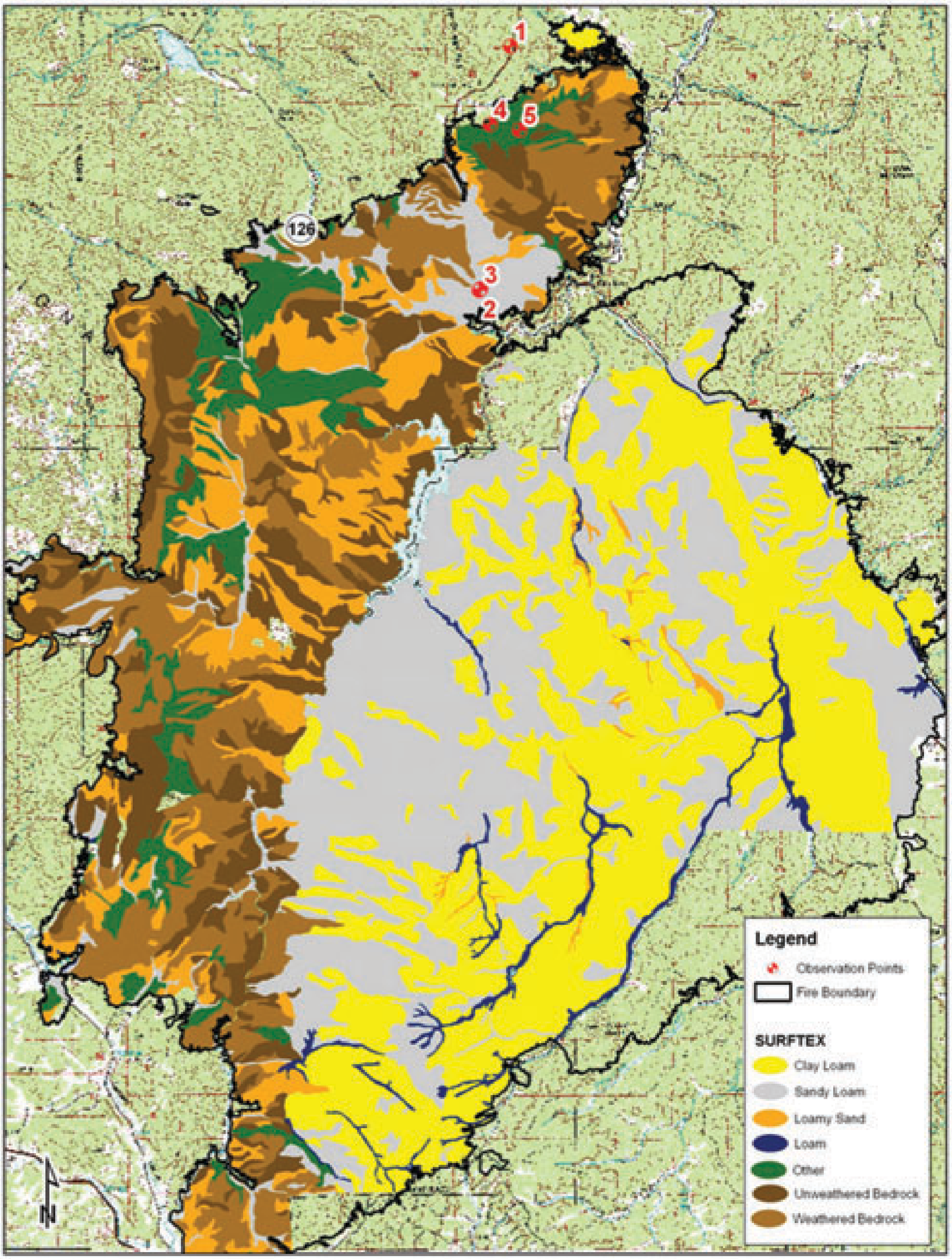

Figure 7—Soils map of Hayman Fire.

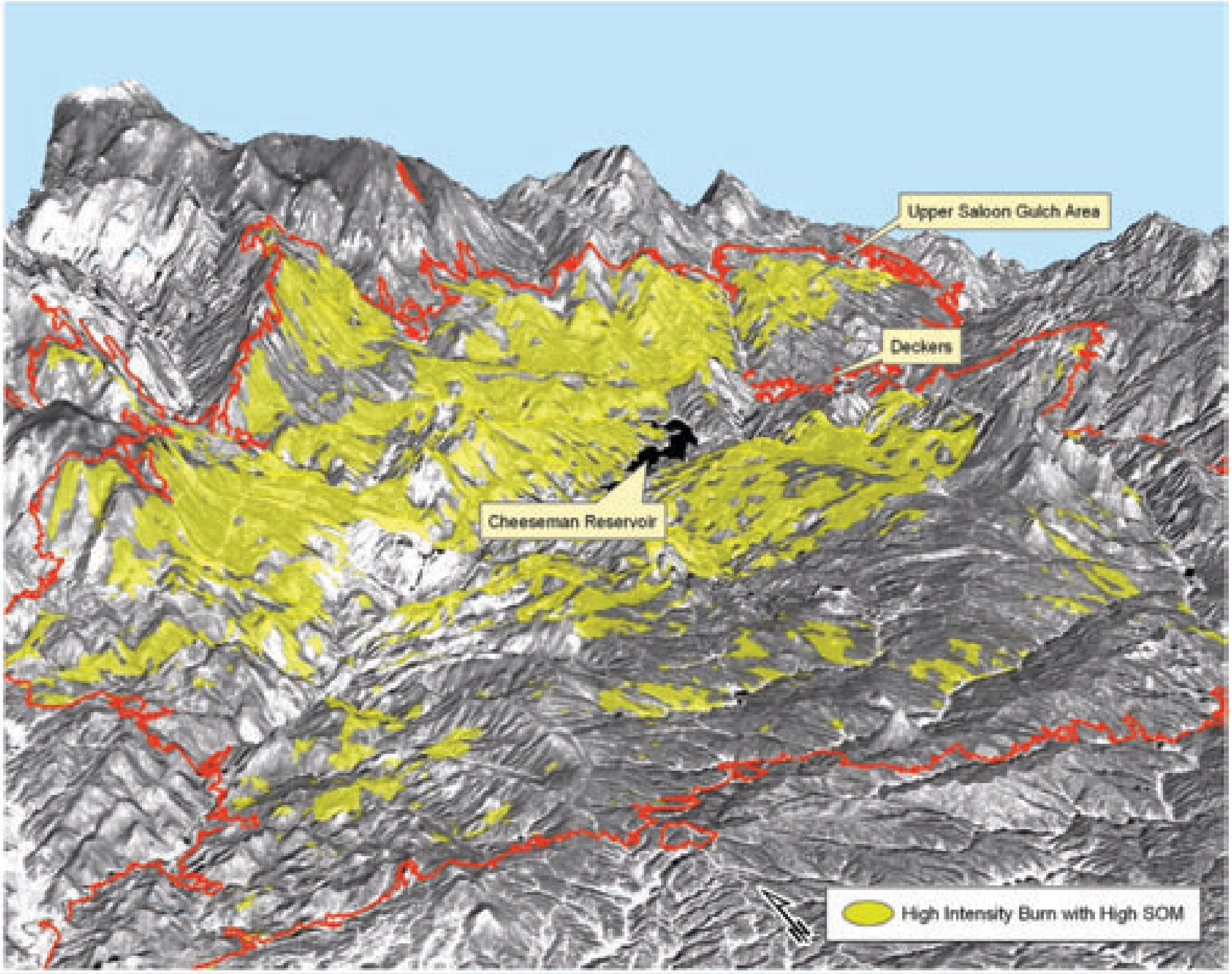

Figure 8—Digital Elevation Model (DEM) of Hayman Fire area draped with burn severity and soil organic matter (SOM).

sediment filling and destroying catchment structures and washing away 90 percent of the seed from aerial reseeding efforts, in addition to other erosion and sedimentation damage. Loss of storage capacity in downstream reservoirs, coupled with impaired water quality for Denver's water supply, resulted in large monetary losses. These conditions combined to produce what is quite likely a worst-case scenario of postfire erosion in the Pikes Peak batholith, which also underlies most of the area burned by the Hayman Fire.

Figures 11 and 12 depict the Upper Saloon Gulch area, where multiyear sedimentation studies were conducted both before and after the Hayman Fire. Figure11 shows the intersection of high SOM with high burn severity, and figure 12 depicts surface SOM levels in the area prior to the burn. Field assessments here confirmed that in high severity fire areas, all surface litter and the organic matter (SOM) in the upper few centimeters of the mineral soil has been destroyed by the fire. In addition, postfire erosion has removed some of the mineral soil (primarily topsoil). Most of the published and unpublished observations that we are aware of, as well as our field measurements and those of other scientists and forest managers, indicate that high severity fires do in fact usually destroy both above and below ground organic material in similar situations.

On the other hand, the threat of erosion from *low severity* fires – either prescribed or wild – is relatively small, as by definition these fires do not completely consume the surface litter layer (and therefore do not

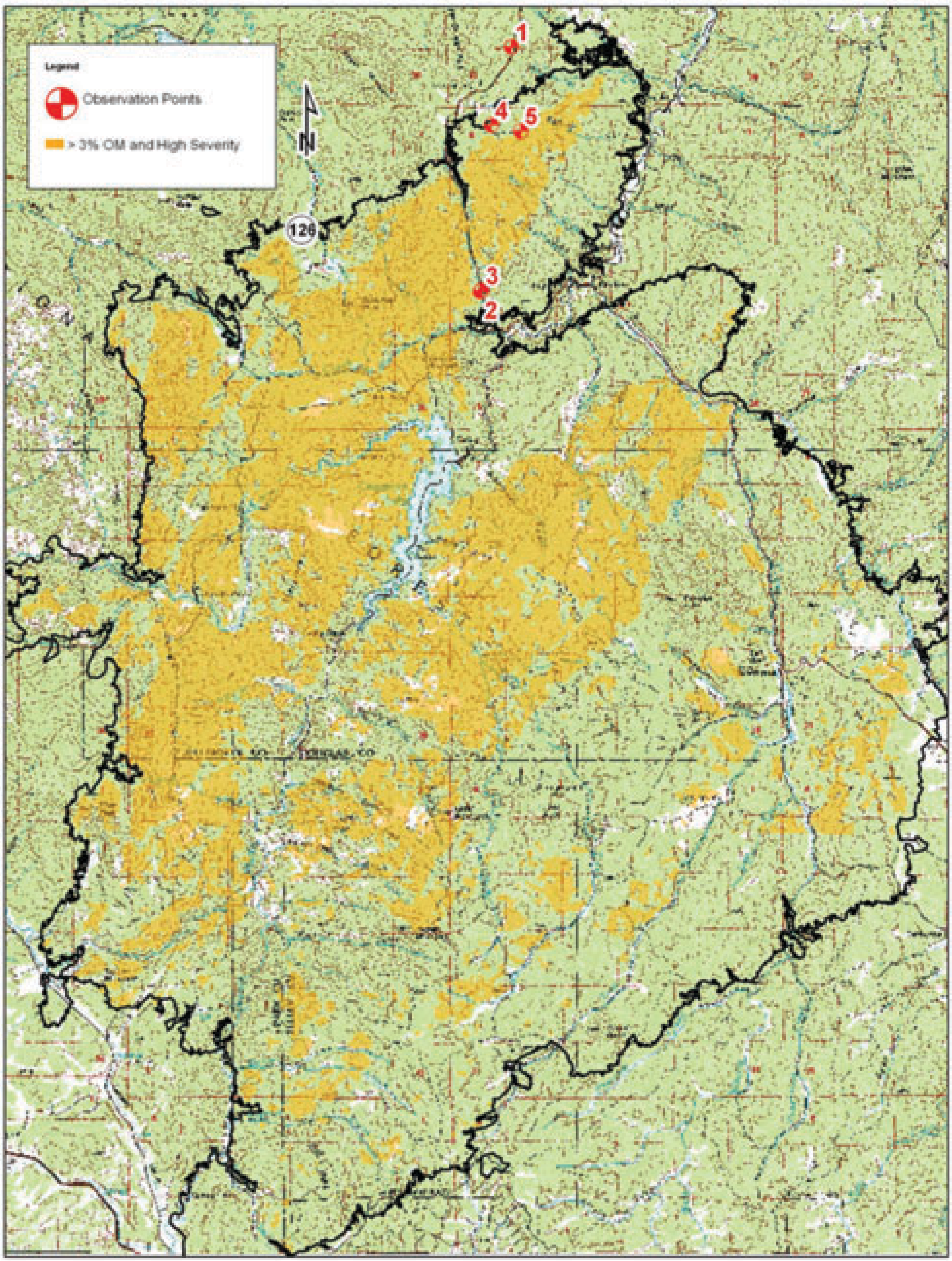

Figure 9—Extent of intersection of high burn severity and high soil organic matter.

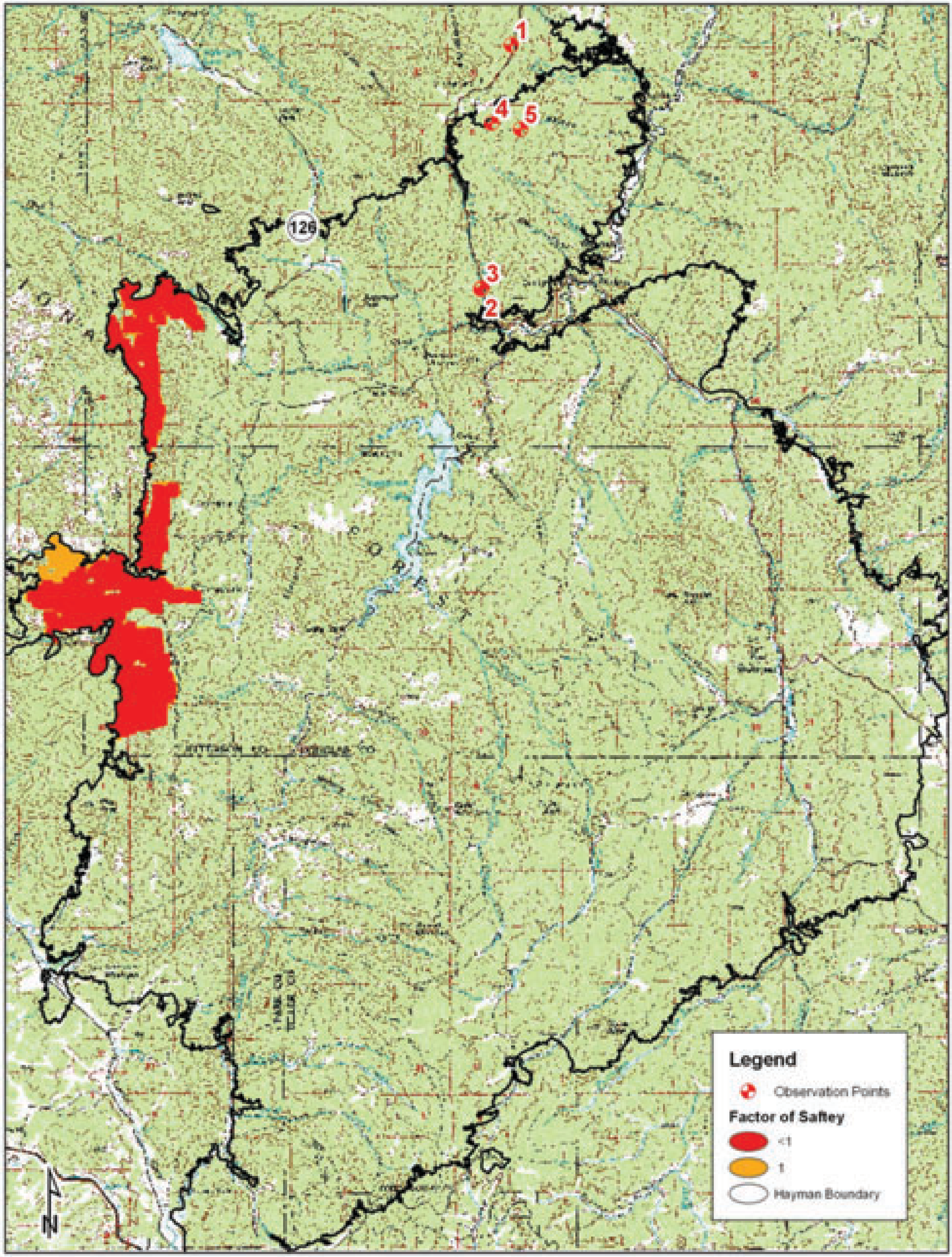

Figure 10—Map output from the slope stability model analysis. Areas shown in red fall below the threshold value of 1.

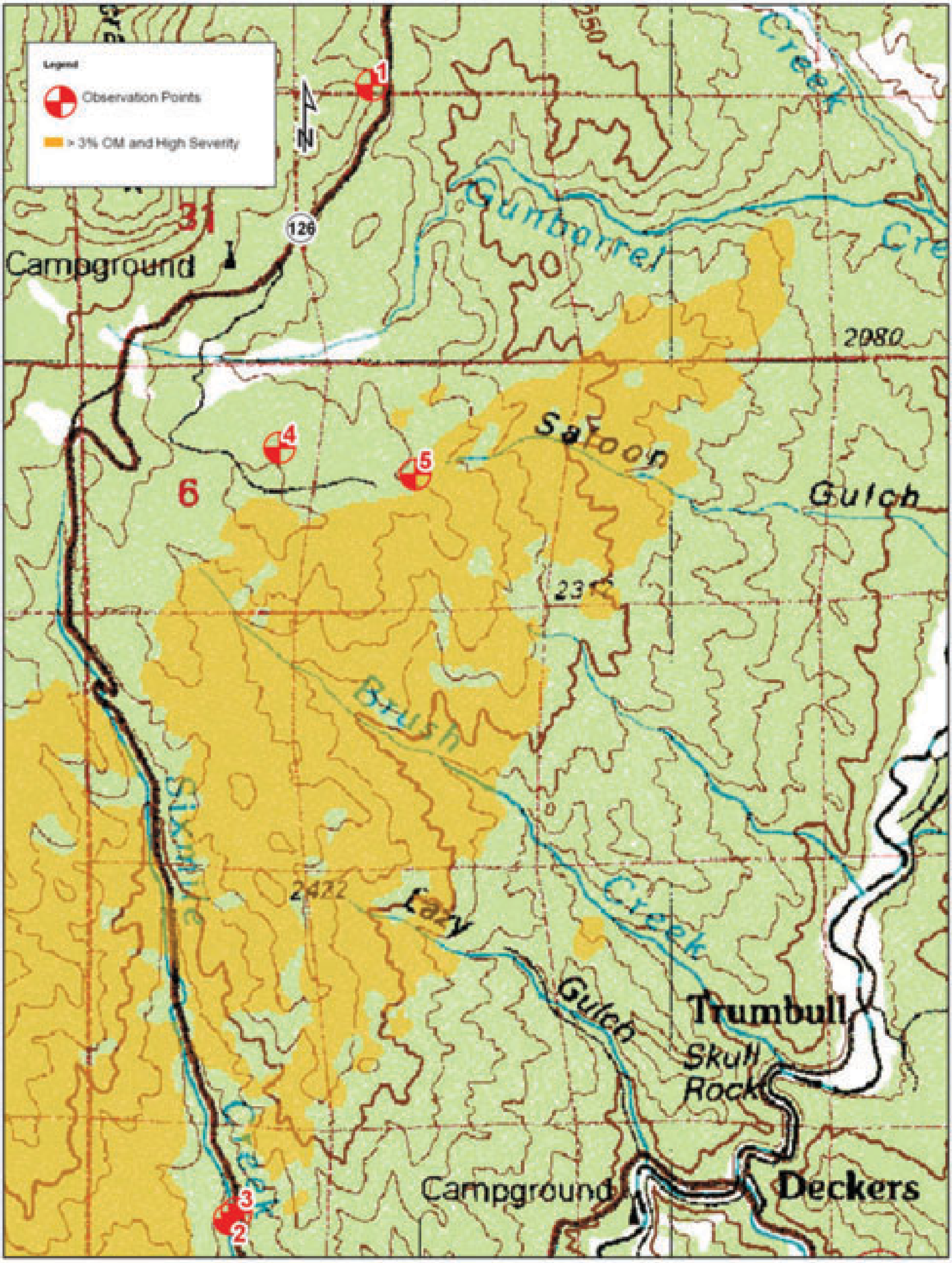

Figure 11—Intersect of soil organic matter and severity.

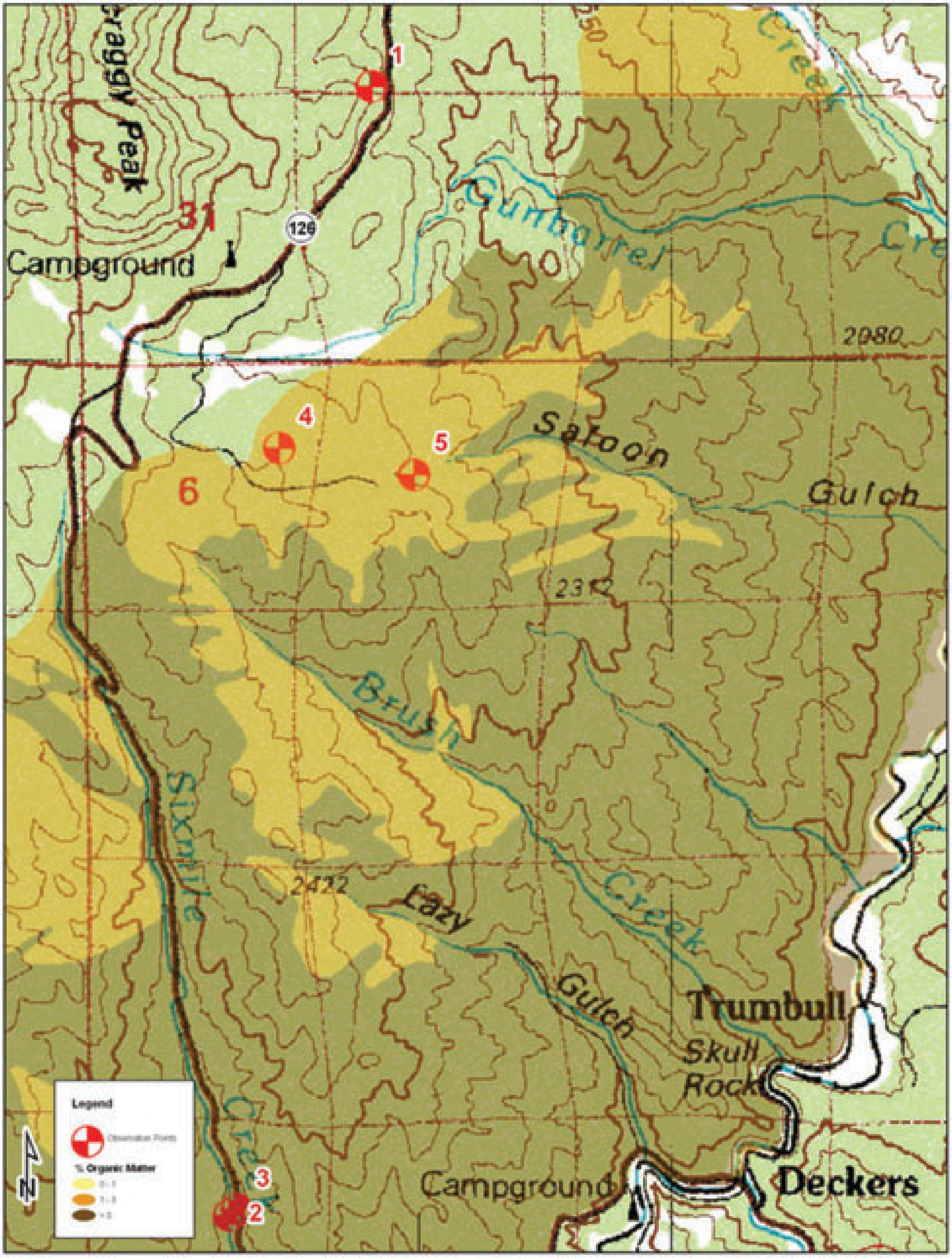

Figure 12—Soil organic matter in Saloon Gulch area.

consume the organic matter and nutrients in the surface mineral soil either). Areas burned at low severity are often found in a complex mosaic with unburned areas, reducing the overall litter and topsoil loss from these areas.

Similarly, areas burned at *moderate severity* may pose a lesser, shorter term threat than high severity burn areas to terrestrial and aquatic resources, as the mineral soils in these areas are not visibly altered and recovery is relatively rapid (Benavides-Solorio 2003). In the Hayman Fire moderate intensity burn areas, much of the litter layer has been burned but some still remains, and vegetation understory recovery is expected to be relatively rapid, thus protecting the soil from erosion and restoring soil fertility.

Most available literature suggests that high-severity wildfires can increase postfire erosion rates by one or more orders of magnitude. This increase in erosion has been documented in pine forests in South Africa (Scott 1993), eucalyptus forests in Australia (Prosser and Williams 1998), chaparral in the Southwestern United States (Laird and Harvey 1986; Rice 1974), coniferous forests in Yellowstone National Park and central Washington (Helvey 1980; Meyer and others 1995), and ponderosa pine in the Colorado Front Range (Morris and Moses 1987). Recent sediment yield studies in Colorado Front Range forests (Benavides-Solorio 2003; Moody and Martin 2001a) reported more than seven times as much sediment from plots that were severely burned compared to plots that were moderately burned. The precise causes of the observed increases are generally not well documented. Contributing processes include the pulverization of the soil due to the burning of the soil organic matter and accompanying breakdown of soil aggregates, increased rain splash due to the loss of the protective litter layer, destruction of the microbial crust, soil sealing, increased dry ravel, and development of a less permeable hydrophobic layer 1 to10 cm below the surface. Many of these processes interact to change the hydrologic regime from little or no surface runoff in the unburned condition to large amounts of overland flow from moderate to high intensity rainfall events.

Sediment deposition occurs when there is a reduction in transport capacity, and this adversely affects most of the designated beneficial uses of water, including reservoir storage, fish habitat, and domestic water supply. This sequence of wildfire, increased runoff, erosion, and downstream sedimentation is of great concern because past land management practices have created excessive fuel loadings in many areas of the Western United States. The Hayman Fire is simply one of the most recent and dramatic examples of erosion and sediment deposition affecting the soil and water resources of the Front Range.

Evidence also suggests, in contrast to severe wildfires, low (and even moderate) severity fires generally do not result in a corresponding increase in runoff and erosion (Robichaud and Waldrop 1994; Benavides-Solorio 2003). Certainly, runoff and erosion from moderate severity burn areas are expected to be significantly less than from high severity burn areas. Thus, if the threat of severe wildfires was reduced through fuel modifications, then most likely the associated risks of flooding, erosion, and downstream sedimentation would also be reduced. The identification of areas with the highest erosion and sedimentation hazards on both landscapes and sites could display and quantify the potential benefits from reducing the risk of severe wildfires. Limited data from an ongoing study indicate that forest thinning is unlikely to cause substantial increases in runoff and erosion (Libahova and MacDonald 2003).

Two other important factors responsible for accelerated erosion following forest fire are the loss of canopy and ground cover (especially forest floor litter) and the increased probability of soil water repellency, especially in sandy soils under coniferous forest cover (Morris and Moses 1987).

The National Forestry Manual published by the USDA Natural Resource Conservation Service (NRCS) in 1997 employs the K factor (representing soil erodibility) from RUSLE and breaks out four slope categories that are combined to develop a soil rating for potential erosion hazard. The guidelines in this manual are useful because of the standardized national application, the availability of data, and the functionality to be manipulated within a GIS framework and on a watershed basis. (The K factor is the soil's inherent susceptibility to erosion and is closely related to infiltration capacity and structural stability; which factors are in turn influenced by surface soil texture, surface organic matter content, permeability, and other variables specific to soil type.) K factor values typically range from near zero to 0.6, with low values representing low soil erodibility and high values reflect high erodibility. However, we did not apply the RUSLE model to the Hayman Fire because there is a lack of field data at this time to supply input parameters and calibration of the model.

To obtain field data for immediate assessment and as input to empirical erosion hazard models, recent research has been conducted in northern Colorado Front Range forests (Rough and others 2003; Kunze and Stednick 2003; Benavides-Solorio 2003; Hughes and others 2003; Libohova and MacDonald 2003; Pietraszek and MacDonald 2003). Initial findings indicate that *percent cover* and *rainfall erosivity* are two important controlling variables, which in one study explained nearly two-thirds of the observed variability in hillslope-scale erosion rates from both prescribed and wild fires

(Benavides-Solorio 2003). Soil texture was only a minor factor, probably due to the fact that most forest soils in the study areas (and many Front Range forests as well) are at least 60 percent sand and less than 10 percent clay. Many soil textures in the Hayman Fire fall within this range, with some areas in the southeast portion of the burn being less sandy. There are not yet enough hillslope-scale erosion data collected to know whether the existing empirical models can be directly applied to predict soil losses and sediment deposition with a high degree of accuracy.

The USDA Forest Service Watershed Conservation Practices Handbook (FSH 2509.25) establishes standards and design criteria intended to protect soil (soil productivity and sediment control), aquatic (hydrologic function and water quality), and riparian system functions on National Forest lands. Soil quality has been defined as "the capacity of a specific soil to function, within natural or altered land use boundaries, to sustain or improve plant and animal productivity, water, air quality, and human health and habitation" (National Cooperative Soil Survey Soil Quality Committee 1995). Soil health is defined as "the condition of the soil with reference to its inherent quality and ability to perform vital ecosystem functions." Those vital functions are to: (1) sustain biological activity, diversity, and productivity; (2) partition water, energy, and solute flow; (3) restore and cycle nutrients and other materials; (4) filter, buffer, immobilize, and detoxify organic and inorganic materials; and (5) support structures and protect archeological treasures.

Removal or reduction in surface vegetation cover and formation of less permeable soils can lead to increased surface runoff and overland flow that acts as a force to cause the detachment and transport of sediment. These sediment-laden flows may then induce sheet wash, rill, and gully erosion, and cause mass movements such as debris torrents and flows. As mass movements travel through the channel network, they can cause intense bank scour and erosion, which increases the volume of sediment delivered to downstream areas. Ultimately, the increased surface flow relative to infiltration and subsurface flow can result in downstream flooding and damage to life and property.

Reduction in soil organic matter increases the susceptibility of soil to surface sealing and compaction. The resulting decrease in infiltration will increase overland flow that can lead to rill and gully erosion.

Impact of the Hayman Fire on Key Soil Properties

Changes in soil properties due to fire in the Hayman Fire area were estimated from detailed studies conducted on other recent fires in the Colorado Front Range (Huffman and others 2001) and a limited amount of data from the adjacent Schoonover Fire. Areas severely burned were expected to have a complete loss of the protective litter layer and a loss of the organic matter in the top few centimeters (that is, 0 to 3 cm). Also in these areas a relatively strong water repellent layer may extend from a few centimeters below the mineral soil surface to as much as 10 cm below the surface. This water repellent layer has been observed in the adjacent Schoonover Fire by the critical surface tension test as used by Huffman and others (2001), and it can also be inferred by the large amounts of surface runoff and erosion generated by summer rainfall events after the Hayman Fire. Extensive rilling has been observed on various sites in the northern portion of the Hayman Fire, while prefire observations showed no evidence of rilling in some of the same areas (for example, in the Upper Saloon Gulch area).

Similar effects can be expected in the areas with moderate burn severity, although in these areas the loss of surface organic matter may not be as complete as in the areas with high burn severity. Data from other fires suggest that a fire-induced water repellent layer burned moderately (severity) will be similar in depth and magnitude to those areas burned at high severity (Huffman and others 2001). In contrast, areas burned at low severity will still retain some of the surface litter and most, if not all, of the organic matter in the top few centimeters of the soil. The water repellent layer will be too weak and discontinuous to substantially affect runoff and erosion rates at the hillslope of small catchment scale.

The water repellent layer can be expected to persist for up to 1 to 2 years (Huffman and others 2001). Over the winter this layer is not expected to cause an increase in runoff rates, as the combination of low intensity rainfall events and snowmelt will cause this water repellent layer to wet. Once the soils are wet, the soils cease to be water repellent until they are dry. Preliminary data from the Bobcat Fire in the northern Colorado Front Range suggests that the soil water repellency is largely eliminated at soil moisture contents ranging from about 12 percent in areas burned at low severity to as much as 25 to 30 percent in areas burned at high severity (MacDonald and Huffman, in prep.). The water repellent layer was again be expressed in the summer of 2003 when the soils were dry. By the summer of 2004 the water repellent layer should be substantially weakened and have much less impact on runoff and erosion rates than it did immediately after the fire.

Other Impacts of Fire-Induced Soil Changes in the Hayman Fire

In mid-2001 a project was initiated to evaluate the effects of a proposed thinning project on runoff, erosion, water quality, and channel morphology. Sediment fences were established on 20 swales ranging in size from 0.1 to 1 ha. During the latter half of 2001 and through the winter of 2001 to 2002 no mineral sediment was collected in any of the sediment fences. The Hayman Fire burned all of these sites at severely, and the percent bare soil and ash increased from a mean of 12 to 93 percent (fig. 13). Soil water repellency was measured using the critical surface tension (CST) test (Huffman and others 2001). In this test drops of pure water are placed on the surface, and if these do not infiltrate within 5 seconds, drops with successively higher concentrations of ethanol are applied. Because ethanol reduces the surface tension, the first solution that readily infiltrates into the soil is considered the critical surface tension. Previous work has shown that the CST test is both faster and less variable than the more common water drop penetration test (Huffman and others 2001). Data from sites burned at high severity and nearby unburned sites show that the Hayman Fire increased the strength of soil water repellency from the soil surface to a depth of approximately 6 cm (fig. 14). The loss of soil cover, when combined with the development of a water repellent

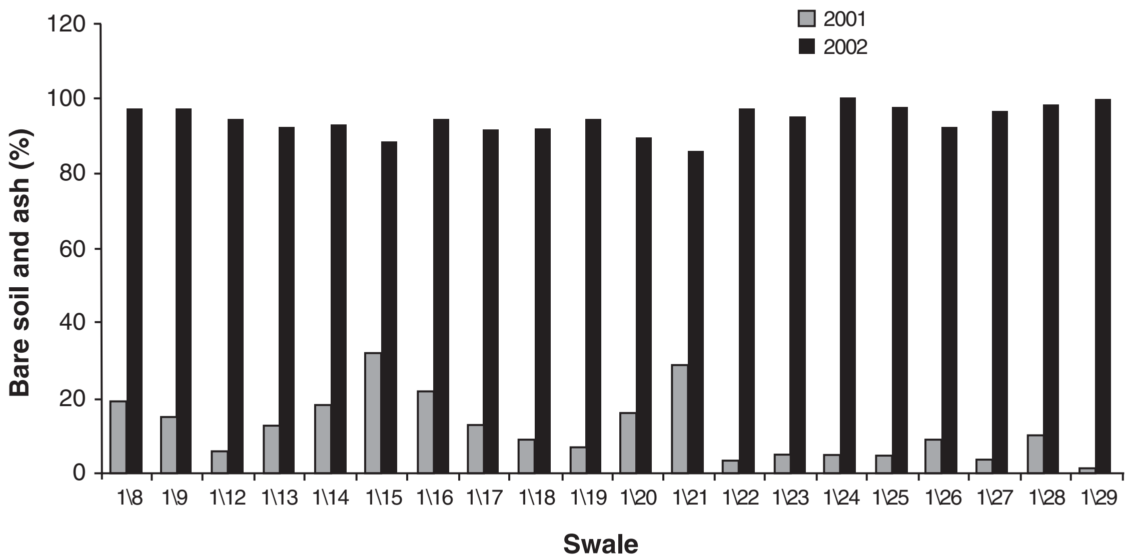

Figure 13—Percent bare soil and ash on 20 swales in Upper Saloon Gulch in October 2001 and in July 2002 after the Hayman Fire.

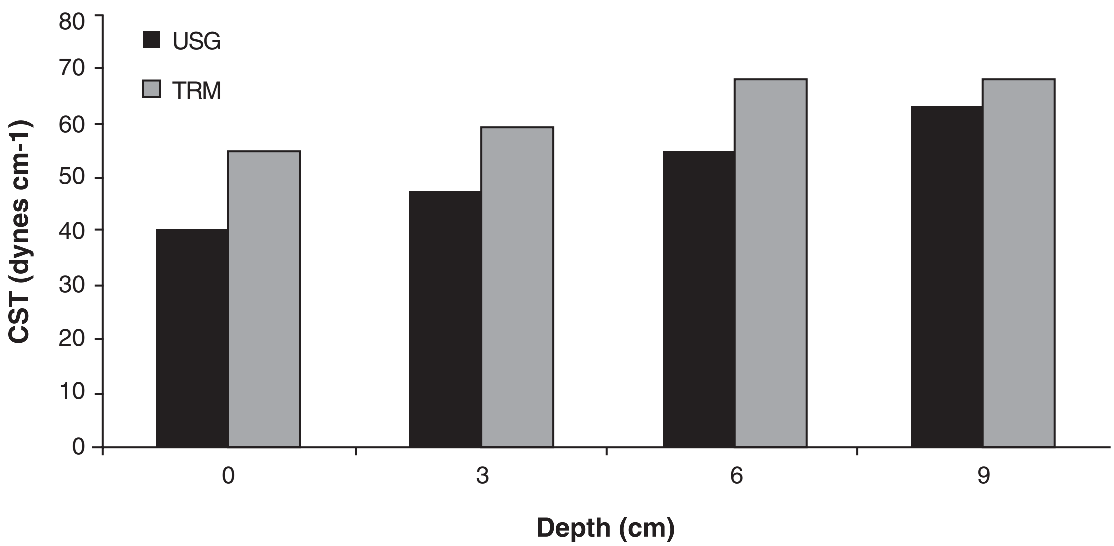

Figure 14—Mean soil water repellency in the burned swales in Upper Saloon Gulch (USG) in July 2002 after the Hayman Fire compared to unburned areas in Trumble Creek (TRM). Lower values indicate stronger soil water repellency.

layer, greatly increases the potential soil erosion rates. We observed an average erosion rate of approximately 0.6 kg/m2 (nearly 3 tons/acre) on our 20 study plots from a single storm of 11 mm of rain in 45 minutes (fig. 15). The limited amount of data collected in summer 2001 – prior to the fire – strongly indicate that this storm would not have generated any measurable surface runoff or erosion. High runoff and erosion rates were observed from other convective rain storms, but the total erosion rate after the Hayman Fire was relatively low because the rainfall in June, July, and August was less than 50 percent of the long-term average (fig. 16). Most of the rainfall in September fell at low intensities (less than 10 mm per hour) and therefore did not generate as much erosion as the convective storms in July.

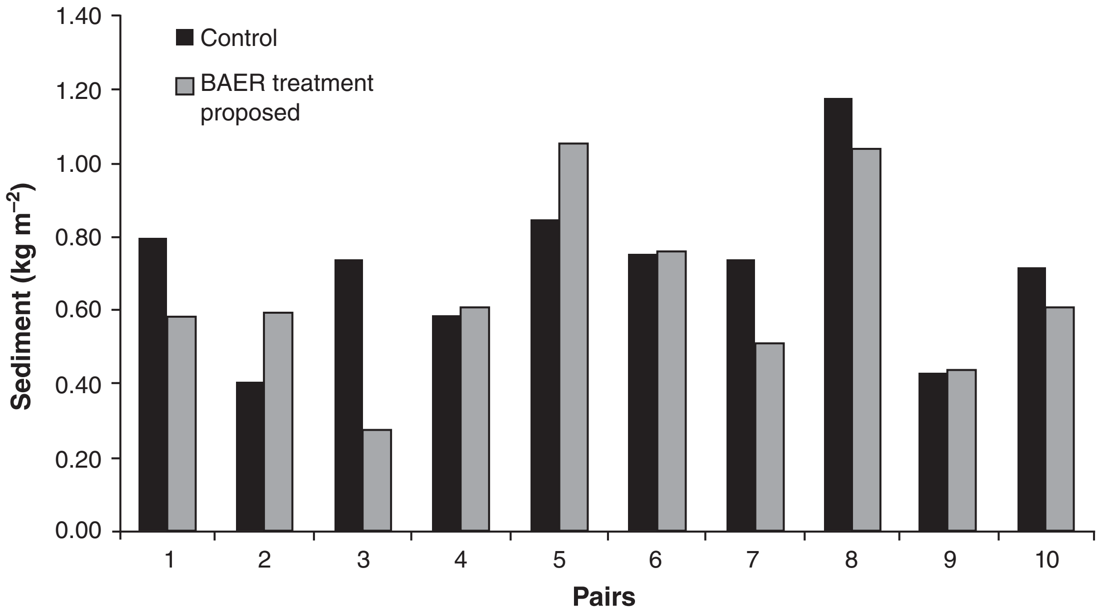

Figure 15—Sediment production from 10 pairs of swales in Upper Saloon Gulch from an 11 mm rainstorm. One swale of each pair was designed to be a control for a burned area emergency rehabilitation treatment (BAER). A rainstorm occurred before the treatments could be applied.

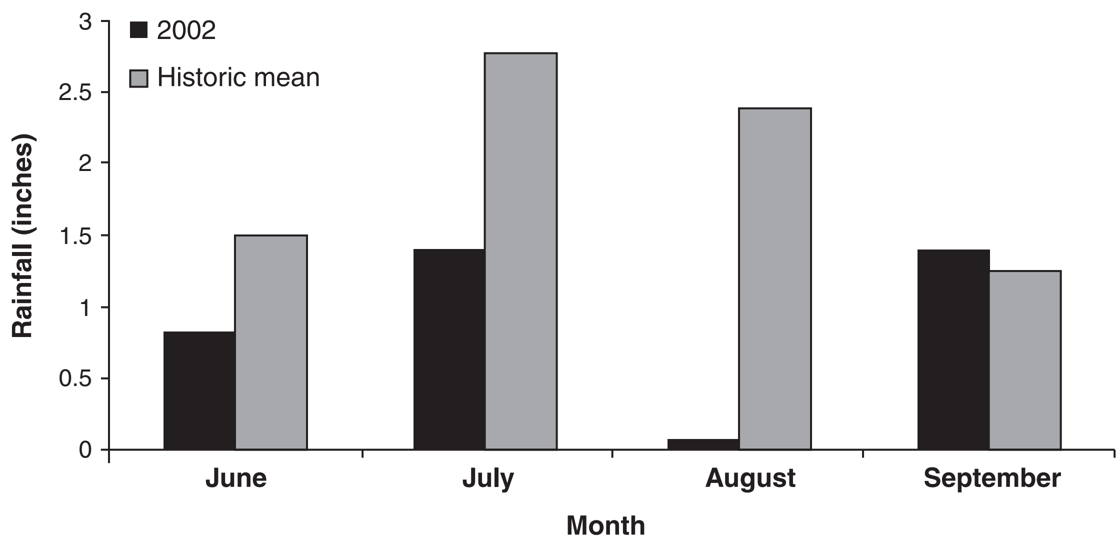

Figure 16—Monthly rainfall at Cheesman Reservoir for June-September 2002 versus the long-term mean.

Relatively little erosion occurred over the winter, and this is probably due to two reasons. First, the water repellent layer had wetted up, and at higher soil moisture contents (for example, greater than about 20 to 30 percent) the soil is no longer water repellent. Second, the rate of snowmelt is much less than the rainfall rate from summer convective storms, so the snowmelt all infiltrates into the soil instead of generating infiltration-excess overland flow.

Percent cover was remeasured in April 2003 and showing that there has been little reduction in the amount of bare soil since late summer 2002. The lack of cover indicates that the areas burned at high severity are still at high risk for high runoff and erosion rates from convective rainstorms in summer 2003. In contrast, nearby sites that were subjected to thinning show only a small increase in the amount of bare soil, and we therefore expect little or no increase in sediment yields from these sites.

Other recent studies have shown that soil erosion rates are strongly correlated with the proportion of the soil surface covered by organic materials (Benavides-Solorio 2003; Wagenbrenner 2003; Wagenbrenner and MacDonald, in prep.; Pietraszek and others 2003). Sites burned with high severity typically have less than 10 to 15 percent cover in the first summer after burning, and similar values have been measured at numerous sites in the northern part of the Hayman Fire. Percent cover increases over time, but in the absence of any rehabilitation treatments, the percent cover was expected to be low (such as less than 30 percent) in summer 2003, the year after the fire, especially given a continuing drought in Colorado. Erosion rates in the second summer may be nearly as high as in the first summer after burning, although the values will be highly dependent on the magnitude and intensity of the summer thunderstorms. The greatest reduction in erosion rates occur as the percent cover increases from about 30 to 70 percent. Data from other sites suggest that erosion rates should substantially decline by the third summer after burning, and approach background levels within 4 to 5 years. Erosion from winter storms is expected to be minimal, as much of the precipitation falls as snow, and rainfall intensities are much lower than for the convective thunderstorms that are characteristic of the summer season.

Areas burned with moderate severity typically have slightly more soil cover in the first year after burning, and they recover more rapidly (Hughes and others 2003). Erosion rates from areas burned at moderate severity have only 15 to 20 percent of the erosion rates from areas burned with high severity. Areas burned with low severity have much more cover, and in the first summer after burning the surface erosion rates from low-severity areas will be only 3 to 8 percent of the erosion rates from areas burned at high severity.

Data from the Bobcat Fire showed that mulching was the only treatment that consistently and significantly reduced erosion rates. In the second summer contour-felling did significantly reduce erosion in some areas (J. Wagenbrenner, USDA Forest Service, personal communication 2002). The primary reason for the immediate effectiveness of the mulch treatment is that it immediately increased the percent cover, compared to gradual increase in percent cover from growing vegetation. Data from a single small rainstorm on the Hayman Fire also suggest that mulching was effective in reducing soil erosion, but the results might be quite different if the study areas are subjected to a much larger storm. In general, rehabilitation treatments are going to be most effective in the small storms and have progressively less effect on reducing runoff and erosion rates with increasing storm size. The other treatment that immediately increases surface cover is hydromulching. Unfortunately this treatment was only installed on our study sites in the Hayman Fire in mid-September 2002, so we have no data yet on its effectiveness. Qualitative observations indicate that some hydromulched areas already have experienced considerable rilling, while in other areas rilling has not occurred, and the hydromulch is still largely intact.

The scarification and seeding treatment applied on the Hayman Fire is likely to be the least effective, as both the mechanical and hand scarification is too shallow to break up the hydrophobic layer, and the seeding has not yet had an effect on soil cover. Erosion data from one storm over four small catchments suggest no difference in sediment production rates between untreated sites and adjacent sites subjected to scarification and seeding. Qualitative observations from the Hi Meadows Fire suggest that scarification facilitated seed germination, but in this case a series of small rainstorms allowed the seed to germinate. The Hayman Fire generally did not receive as much postfire rainfall, and this may explain why the scarification treatments and seeding treatment have not appeared to result in much vegetative cover.

In conclusion, the areas burned at high severity are of greatest concern due to lack of cover and the development of a water repellent layer a few centimeters below the soil surface. Treatments that immediately increase the percent cover are most likely to reduce erosion rates, but these treatments will be progressively less effective with increasing rainfall intensities. Areas burned at moderate severity are also of concern, particularly in the first 1 to 2 years after burning. Erosion rates can be expected to return to near-background levels after 4 to 5 years when the percent cover has increased to at least 60 to 70 percent. Recovery of the stream channels is likely to be much slower, as the headwater channels are incising, and many downstream channels are being buried by large amounts of fine sediment.

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