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# Field Guide for Mapping Post-Fire Soil Burn Severity

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## Abstract

Following wildfires in the United States, the U.S. Department of Agriculture and U.S. Department of the Interior mobilize Burned Area Emergency Response (BAER) teams to assess immediate post-fire watershed conditions. BAER teams must determine threats from flooding, soil erosion, and instability. Developing a post-fire soil burn severity map is an important first step in the rapid assessment process. It enables BAER teams to prioritize field reviews and locate burned areas that may pose a risk to critical values within or downstream of the burned area. By helping to identify indicators of soil conditions that differentiate soil burn severity classes, this field guide will help BAER teams to consistently interpret, field validate, and map soil burn severity.

**Keywords**: BAER, photo series, post-fire mapping, post-fire rehabilitation, remote sensing

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## Introduction

### *Issue and Background*

Post-fire assessments are generally conducted by U.S. Department of Agriculture (USDA) Forest Service or U.S. Department of the Interior (DOI) Burned Area Emergency Response (BAER) teams after large wildfires. A BAER team's primary objective is to rapidly identify post-fire effects and determine whether the wildfire has created unacceptable risk to human life and safety, property, and critical natural or cultural resources. The BAER team may manage risk by recommending treatments for land, channel, road, and trail stabilization and for public safety (Calkin and others 2007; USDOI BLM 2007; Napper 2006; USDA Forest Service 2004).

A map that reflects the fire's effects on the ground surface and soil condition is needed in order to rapidly assess fire effects, identify potential areas of concern, and prioritize initial field reconnaissance. Thus, it is important to develop a soil burn severity map as quickly as possible during the initial post-fire assessment phase. This map identifies the fire-induced changes in soil and ground surface properties that may affect infiltration, runoff, and erosion potential (Parsons 2002). It also enables BAER teams to achieve their primary objective of identifying areas of unacceptable risk to a critical value and where rehabilitation treatments may be most effective (Robichaud and others 2008b; Calkin and others 2007; Robichaud and others 2000).

BAER teams have often struggled with accurately mapping post-fire soil burn severity. This challenge has grown in recent years as larger fires affect multiple jurisdictions, agencies, and landowners. There is a need for consistent methodologies, assessment tools, and terminology that quickly and accurately identify the post-fire conditions. In response, BAER teams are using many geospatial assessment tools to expedite post-fire soil burn severity assessment. However, little standardization of methodology or terminology has occurred in soil burn severity mapping and field verification. This guide provides direction to BAER teams to promote consistency in post-fire soil burn severity mapping. With a field-validated soil burn severity map, BAER teams can more readily evaluate secondary wildfire effects, including increased runoff, erosion, flooding, sedimentation, and vulnerability to invasive weeds, and can predict natural revegetation (Calkin and others 2007).

This field guide clarifies concepts, terminology, context, and use of the soil burn severity map. Field indicators and classification guidelines are also provided for use in mapping. Using this field guide will ensure consistency in map products across ecoregions around the United States. Components of this guide include:

- terminology and definitions,
- the role of remote sensing and geographic information systems (GIS) in BAER assessments,
- guidelines for identifying soil burn severity classes in the field,
- discussion on soil burn severity within general vegetation density models,
- photo series showing representative post-fire soil and ground conditions, and
- field data sheets to assist in data collection for mapping soil burn severity.

This guide provides a reference for ground conditions, soil characteristics, and vegetation density models that most closely match the field setting. Observations can be compared with those in the tables and photos to make a determination of the soil burn severity classification at a field location. This guide presents representative conditions only. Actual ground conditions will vary within the categories.

## *Terminology and Definitions*

Fire effects literature, Incident Management Teams, and post-fire assessment teams use various terms to describe post-fire conditions (Jain and others 2004; Lentile and others 2006). Consistently using proper terms will help avoid confusion and clarify the focus of the BAER team's products. See fig. 1 for an example of a high intensity fire resulting in high soil burn severity. This illustration depicts a scenario where surface and ground fuels are abundant (in other words, high pre-fire vegetation density). The correlation between fire intensity and soil burn severity is not always direct, however, because aside from the *amount* of heat generated, *duration* plays a critical role in fire effects to soil (DeBano and others 1998; Hartford and Frandsden 1992). To clarify their meanings and to minimize confusion about implications of burn severity maps, the following terms are defined (adapted from Scott and Reinhardt 2007):

**Char:** Visual estimate of soil or vegetation burn that is essentially the percent of the surface

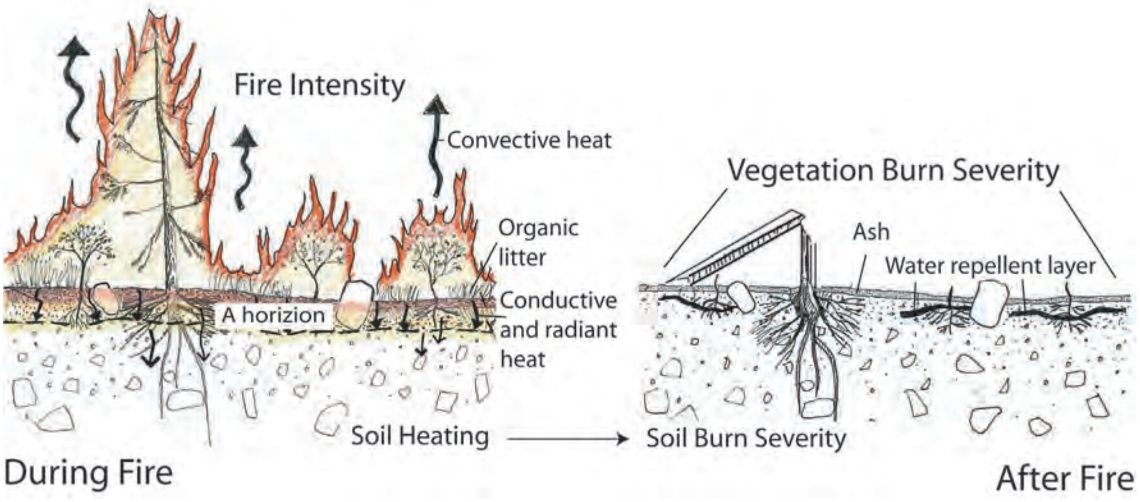


**Figure 1.** Illustrates the effect of fire intensity on above-ground vegetation and below-ground soil properties. Graphic modified by Mike Hankinson, National Park Service.

that has been scorched (blackened). Soil char is an indicator of potential root damage or soil heating (Ryan and Noste 1985).

**Fire effects:** The physical, biological, and ecological impacts of fire on the environment (National Wildfire Coordinating Group 1996). Two types are often discussed: first-order fire effects (direct effects of the combustion process on the environment) and second-order fire effects (effects that occur after some time and are often caused by interaction of fire-caused stress with other factors).

**Fire intensity:** The amount of energy or heat release per unit time or area during the consumption of organic matter (Keeley 2009). Byram (1959) defined the term as "the rate of energy or heat release per unit time, per unit length of fire front, regardless of its depth." Other measures of fire intensity include fireline intensity, reaction intensity, and total fire flux, all of which refer to the actual burning event (White and Pickett 1985). Fire intensity is a real-time burning measurement and does not directly indicate the effects of the fire on the vegetation or soil or the subsequent ecosystem response (Keeley 2009). For example, a high intensity fire that exhibits extreme fire behavior (such as high flame length, rapid rate of spread, or overstory crown consumption) might result in low- or moderate-degree effects on the soil (soil burn severity) due to short heat residence time. Typical examples are crown fires in forests or shrub or grassland fires. Conversely, a low intensity fire (smoldering log) can produce intense heat and can be long duration, resulting in high soil burn severity in the area under the log, tree root channels, or woody debris concentration.

**Ground cover:** Ground cover refers to effective organic cover as it pertains to mitigation of runoff and erosion and includes litter, duff, and woody debris. It may also be called "soil cover" or "organic ground cover."

**Soil burn severity:** The affect of a fire on ground surface characteristics, including char depth, organic matter loss, altered color and structure, and reduced infiltration (Lentile and others 2006; DeBano and others 1998; Ryan and Noste 1985). The classification of post-fire soil condition is based on fire-induced changes in physical and biological soil properties. During post-fire assessments, there has been an intentional effort to use the term "soil burn severity" to differentiate post-fire soil properties from fire effects on vegetation (such as tree mortality) and/or general fire effects on long-term ecosystem health.

**Soil heating:** An increase in soil temperature as a result of heat transfer from the combustion of surface fuel and smoldering combustion of organic soil horizons. Because of the variability of fuel consumption, soil heating typically is non-uniform across landscapes. In many cases, the highest soil temperatures are associated with high fuel consumption and/or complete duff/forest floor consumption, which are affected by the duration and intensity of the fire and are related to the pre-fire fuel moistures. The two components of soil heating that affect soil burn severity are maximum temperature achieved and duration of heating.

**Vegetation burn severity:** The effect of a fire on vegetative ecosystem properties, often defined by the degree of scorch, consumption, and mortality of vegetation and the projected or ultimate vegetative recovery (Lentile and others 2006; Morgan and others 2001). The vegetation burn severity of a fire depends on the fire intensity and the degree to which ecosystem properties are (or are not) fire resistant. For example, a fire of exactly the same fireline intensity might kill thin-barked trees but have little effect on thick-barked trees, or it may root-kill rather than canopy-kill trees, which would result in greater mortality than initially observed.

**Water repellent soils (water repellency):** Resistant to water penetration; not wettable. With fire-induced soil water repellency, soil particles are coated with hydrophobic compounds. When organic material burns at high intensity, the hydrophobic organic compounds often vaporize, and some of the vaporized compounds move down into the soil. When the vapors reach a soil depth where the temperature is low enough, the hydrophobic compounds condense and coat the soil particles at that depth—generally 0.25 to 2 inches (0.5 to 5 cm) below the surface and frequently only in a thin (< 1 mm) layer at the immediate soil surface. Water repellency is spatially variable across the landscape and is correlated to soil type, soil particle size, organic matter content, and depth of the litter and duff layer on the soil surface and soil moisture (MacDonald and Huffman 2004; Doerr and others 2009). See Appendix C for more information on how to measure water repellency.

## The Role of Remote Sensing and GIS

The tables and photos in this field guide (beginning on page 12) are useful for mapping soil burn severity, whether the mapping is being done entirely by hand or if the mapping includes the use of remotely-sensed images. This mapping does not require remote sensing or GIS; however, both technologies are commonly used on large wildfires. Depending on availability of resources, access, size, and time frame, some fires are mapped fastest by hand. For example, a 1000 acre (400 ha) fire with sufficient access may be a good candidate for a post-fire assessment done solely via ground and aerial observations. Waiting for a satellite overpasses to image a fire may jeopardize a BAER team's ability to complete its assessment quickly.

For larger and more inaccessible fires, remote sensing and GIS can greatly improve the speed, precision, and accuracy of post-fire mapping efforts. However, soil burn severity mapping should never be done solely through the use of remote sensing classifications and without proper field verification (Parsons 2002; Hudak and others 2004). Ecosystems and fire behavior are variable enough that field observations and refinement of the remote sensing classifications are both necessary. Once the initial image classification has been done, the soil scientist or other specialist must verify the soil conditions in the field before the entire team can use the map.

### *Burned Area Reflectance Classification (BARC)*

Since 2002, the USDA Forest Service Remote Sensing Applications Center (RSAC) in Salt Lake City, Utah, and the USGS Center for Earth Resources Observation and Science (EROS) in Sioux Falls, South Dakota, have provided satellite imagery and derived products to BAER teams to help rapidly map soil burn severity on wildfires (Orlemann and others 2002). Among the products typically provided to BAER teams by RSAC and EROS are pre- and post-fire satellite images of the burned area and a preliminary classification that represent landscape change. This product is referred to as the Burned Area Reflectance Classification (BARC) (Clark and Bobbe 2006).

## Creation of the BARC

The BARC is derived from an image transformation algorithm known as the Normalized Burn Ratio (NBR). The NBR uses the near-infrared (NIR) and mid-infrared bands (also called the short-wave infrared [SWIR] band) from the Landsat satellite sensor. The algorithm is as follows:

$$\text{NBR} = (\text{NIR} - \text{SWIR}) / (\text{NIR} + \text{SWIR})$$

Healthy, green vegetation reflects NIR energy. Conversely, NIR response decreases where there is little vegetation. Mid-infrared energy is largely reflected by rock and bare soil, meaning that mid-infrared band values will be very high in bare, rocky areas with little vegetation and low in areas of healthy, green vegetation. Imagery collected over a forest in a pre-fire condition will have high near-infrared band values and low mid-infrared band values, while imagery collected over a forest after a fire will have low near-infrared band values and high mid-infrared band values.

Many researchers have used a single-scene NBR (López-Garcia and Caselles 1991) and a change detection approach based on the NBR called the differenced Normalized Burn Ratio (dNBR) (van Wagtendonk and others 2004) in burn mapping projects. The dNBR is simply an image differencing between a pre-fire NBR and a post-fire NBR, which are ideally one year apart for vegetation and atmospheric consistency:

$$\text{dNBR} = \text{NBR}_{\text{pre-fire}} - \text{NBR}_{\text{post-fire}}$$

In general, the dNBR is a useful and accurate tool for burn severity mapping (Brewer and others 2005; Cocke and others 2005; Miller and Yool 2002). Nearly all BARC layers are created from the dNBR. Other algorithms are occasionally used simply due to availability (or lack thereof) of spectral bands in the post-fire satellite or airborne imagery used for the assessment.

## Using the BARC

The BARC is not considered a soil burn severity map until it has been field verified and, if necessary, refined to better represent soil and ground conditions. The BARC begins as a continuous raster GIS layer that is classified into four colors that represent the four burn severity classes: unburned is dark green, low is light green, moderate is yellow, and high is red. BARC values are scaled 0 to 255; low values indicate the least burned areas, and values increase as burn severity increases. Some users may find the BARC, as applied to the delivered product, to be a good fit for their wildfire. It can be very accurate in areas of densely forested ecosystems where variation in vegetation type and density are minimal. When no edits are needed, as determined by field verification, the BARC may be renamed the "soil burn severity map."

More often, however, the thresholds applied to the delivered BARC may not be a good fit to the observed post-fire soil and ground conditions. By nature, satellite images and their derived products such as the BARC are reflective of the vegetative condition because that is the uppermost layer or what the satellite "sees." Adjustments to the BARC classes are necessary to produce a map product that is reflective of the soil conditions. Plotting the field observations of soil and ground conditions using GPS coordinates as a data layer overlaid on the BARC allows the user to see how closely the BARC classes match independent and unbiased field observations. Many BAER team members with basic GIS skills find they can adjust the BARC to quickly create a map that represents their observed soil and ground conditions by making simple adjustments to the BARC threshold values. This is called systematic editing–changing the BARC thresholds across the entire fire. Systematic editing works well in situations where vegetation and other site factors produce a fairly predictable distribution of soil burn severity patterns across the landscape. To make systematic changes to the BARC in ArcMap (Environmental Systems Research Institute, Inc. [ESRI], Redlands, CA), team members can simply open the symbology tab within the properties of the BARC layer and adjust the thresholds between the various severity classes. If, for example, field observations indicate the BARC (as delivered) overestimates high severity across the entire fire, an analyst can adjust the breakpoint between moderate (yellow) and high (red) to include more yellow pixels. Common starting points for BARC thresholds are 0 to 75 (unburned), 76 to 109 (low), 110 to 187 (moderate), and 188 to 255 (high). If the high severity in the delivered BARC is overestimated, the user may lower the break between moderate and high from 188 to 170, for example.

Other situations may require edits to localized areas because the imagery used to create the BARC may have problems that cause classification confusion. Clouds, snow, smoke from surrounding fires, or large water bodies within the burn scar (fig. 2) can create inconsistencies in the BARC. There may also be cases where the geology-soils-vegetation-topography interactions are so complex that systematic adjustments do not work well for the entire burned area. In these instances, BAER team members can make soil burn severity adjustments through aerial or ground observations and then integrate those observations into the BARC using GIS.

Another GIS technique that can be used to refine the BARC is to create an overlay with the pre-fire vegetation classes. This can help account for pre-fire vegetation densities and types that

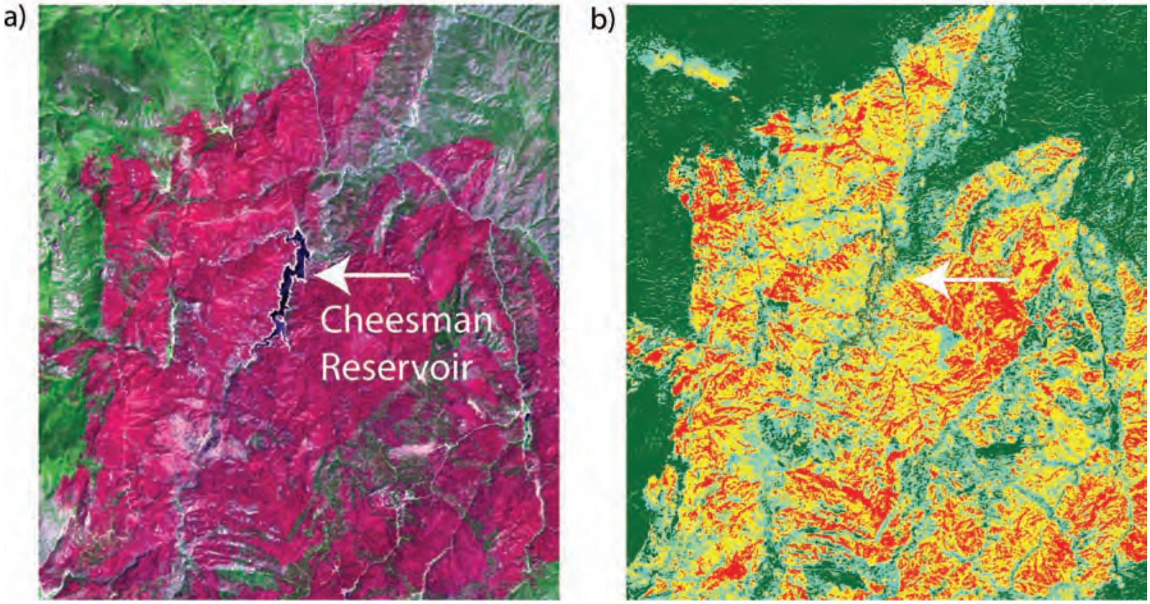


**Figure 2.** Large water bodies within the fire perimeter, like Cheesman Reservoir in the 2002 Hayman Fire Landsat imagery (a), confuse the BARC (b) and should be masked out.

can affect the BARC classification. An overlay of timber sales or cut blocks may also be useful for changing some areas of the BARC from high to moderate or low soil burn severity. In this case, BAER team members can use GIS layers and a pre-fire vegetation classification to reclassify areas of high burn severity on the BARC into whatever is appropriate based on the soil and ground condition data gathered (Appendix B). An example BARC mapping exercise of a mixed conifer/mountain grassland fire that was edited by BAER team members based on pre-fire vegetation is illustrated in Appendix D.

It is important for BAER team members to consider the dates of the satellite imagery used to create the BARC. Though analysts at RSAC and EROS try to use image pairs (pre- and post-fire) that match each other well (ideally one year apart and similar dates), pairs may sometimes span multiple years. If there have been management activities on the landscape between the dates of the imagery used, those activities may influence the severity mapping results. For example, logging activities that occur between the pre- and post-fire images used to create a BARC will likely be classified as high severity. The BARC will assume that the fire in the area of the logging activity was a stand-replacing event when, in reality, the forest structure changed due to management activities prior to the fire event. The BARC assumes all things are equal on the landscape between pre- and post-fire imagery with the exception of the wildfire. BAER teams need to be aware of these potential misclassifications.

RSAC hosts an annual interagency training where BAER teams are taught to understand the BARC, make systematic and localized edits, and use the edited layer in additional modeling. Training materials and information can be found at http://www.fs.fed.us/eng/rsac/baer/training.html.

### *Other Derived Products*

BAER teams are sometimes asked to make an assessment of the vegetation condition following the wildfire. In this case, related products like the Rapid Assessment of Vegetation Condition after Wildfire (RAVG) suite contain more appropriate geospatial layers (www.fs.fed.us/postfireveg-condition). The RAVG project creates maps that relate vegetation effects such as percent change in basal area, canopy cover, and vegetation burn severity. RAVG usually maps fires within 30 days of fire containment (special requests are possible for faster delivery). In addition, the Monitoring Trends in Burn Severity (MTBS) project can provide historical fire severity information in an area that the BAER team is working (www.mtbs.gov). The MTBS project is a nationwide effort to map the vegetation burn severity of all large fires (greater than 1000 acres, 400 ha in the West and 500 acres, 200 ha in the East) between 1984 and present, regardless of vegetation type or land ownership. MTBS usually maps fires one year after they burn.

## Assessment Guidelines

The BARC can be used to identify and characterize preliminary soil burn severity classes. From this initial map, BAER teams can make a paper copy of the remote sensing image provided or another map base, make field visits, and complete the BAER Field Data Sheet (Appendix B). Team members should systematically collect soil information (ground cover, ash color and depth, soil structure, condition of roots, and water repellency) for each soil burn severity class and record locations of data points on a map or using a GPS unit. Once team members get a sense of how the soil burn severity classes are arrayed on the landscape (Key and Benson 2005), they can begin to compare the BARC to the soil and ground condition observations to determine its accuracy. If several specialists are assisting in the validation process, ensure that the group is calibrated using the same procedure. After compiling assessments from the various specialists and comparing these field evaluations to imagery and map data, the team can develop a soil burn severity map from the BARC that is consistent with fire effects science and that meets the needs of the BAER team in assessing runoff and erosion potential.

In some cases, remote sensing imagery and the BARC may not be available to assist in mapping. This field guide is also appropriate as a reference for hand mapping. This section presents a brief description of some important concepts to keep in mind when mapping either by hand or with a BARC map and steps in mapping soil burn severity. More detail can be found in Appendix A.

The ability to map effectively depends on the mapper's ability to examine the burned landscape, determine relationships of important contributing factors, make predictions about how and where conditions occur on the landscape, and create polygons representing those conditions. Concepts such as map unit composition, purity, scale, and intended use are all important to understand. These concepts affect how and where polygons are drawn and what those polygons represent.

One important consideration is minimum polygon size. In general, a minimum of 40 acres (16 ha) is appropriate, but it may be as large as 100 or more acres (40 ha or more) on large fires or as small as 10 acres (4 ha) in areas of critical values-at-risk. It is also important to determine the distribution and extent of localized fire effects when creating a soil burn severity map as they may not represent the majority of the area mapped and should not disproportionately skew the soil burn severity classification.

The photos in this guide provide visual reference to what are considered "representative concepts" of soil burn severity classes in low and high density vegetation types. These photos should be used as a guide only–they should not be viewed as absolute or all-inclusive. Professional judgment is necessary when interpreting soil and ground conditions, especially in moderate density vegetation systems where no representative photos are provided.

Steps involved in mapping soil burn severity include:

- *Get the big picture.* Survey the area to develop a sense of how "green," "brown," and "black" are distributed in the burned area. Record notes.
- *Gather field information.* Spend time on the ground, take notes, and collect GPS points.
- *Start forming "map unit" concepts.* Learn how terrain, vegetation, and burn indicators relate, and describe each map unit according to observed characteristics.
- *Develop a concept of "map unit purity."* Develop an idea of how homogenous the soil burn severity classes are and include descriptions of the classes in the report.
- *Focus field time in the "black."* Time should be spent where the likely problem areas are, and where the most valuable information will be gained.
- *Draw polygons on a map.* Using the BARC, a post-fire satellite image, or a topo map, delineate the soil burn severity classes on a map. Use the ground data notes to help you decide where lines should go.

# Soils Assessment for Low, Moderate, and High Soil Burn Severity Classes

## *Soil Burn Severity Classes and Vegetation Considerations*

Though this document and geospatial tools such as the BARC are intended to help map fire effects on soils, the first thing that the field observer and the remote sensing imagery "see" is the overlying burned vegetation. Because soil burn severity is a result of multiple site factors, including weather at time of burning, for the purposes of the following vegetation type and density models, we assume that there is a direct correlation between vegetation density and amount of ground fuels (Safford and others 2007). More fuels typically cause longer fire residence time, which may result in greater impacts to the soil and ground conditions. The following matrix shows the correlation between vegetation type, density model, and soil burn severity (table 1). These are guidelines and are not necessarily applicable in all fires.

Information about vegetation density and post-fire vegetation characteristics is useful in classifying burn severity. Likewise, canopy char and color are often used as ancillary indicators of overall burn severity but do not necessarily coincide with soil burn severity. In the following descriptions of low, moderate, and high soil burn severity, canopy color is included to guide field stops and initial assessments.

However, to correctly use the soil burn severity map for its intended purpose (predicting accelerated risk of runoff or erosion), the map must reflect the fire-induced changes in soil and ground conditions. The following description of soil burn severity indicators helps users correctly assess post-fire effects to the soil and ground conditions.

**Table 1.** Matrix of soil burn severity and vegetation type and density models.

| | | **Soil burn severity classes** | | |
|---|---|---|---|---|
| **Vegetation type** | **Density model**[a] | **Low** | **Moderate** | **High** |
| Chaparral | Sparse | C[b] | U | ▨ |
| | Medium | C | C | U |
| | High | C | C | U |
| Forest | Sparse | C | U | ▨ |
| | Medium | C | C | U |
| | High | C | C | C |
| Sagebrush | Sparse | C | U | ▨ |
| | Medium | C | C | U |
| | High | C | C | U |
| Grass | Sparse | C | ▨ | ▨ |
| | Medium | C | U | ▨ |
| | High | C | C | ▨ |

[a] Percent canopy cover for sparse, medium, and high density are approximately defined as: Sparse ≤ 20%; Medium = 20–60%; and High ≥ 60%.

[b] Key: C = common; U = unlikely (but can occur in some circumstances); Gray cells = not applicable/does not occur.

## *Severity Indicators*

**Low soil burn severity**: Surface organic layers are not completely consumed and are still recognizable. Structural aggregate stability is not changed from its unburned condition, and roots are generally unchanged because the heat pulse below the soil surface was not great enough to consume or char any underlying organics. The ground surface, including any exposed mineral soil, may appear brown or black (lightly charred), and the canopy and understory vegetation will likely appear "green."

**Moderate soil burn severity:** Up to 80 percent of the pre-fire ground cover (litter and ground fuels) may be consumed but generally not all of it. Fine roots (~0.1 inch or 0.25 cm diameter) may be scorched but are rarely completely consumed over much of the area. The color of the ash on the surface is generally blackened with possible gray patches. There may be potential for recruitment of effective ground cover from scorched needles or leaves remaining in the canopy that will soon fall to the ground. The prevailing color of the site is often "brown" due to canopy needle and other vegetation scorch. Soil structure is generally unchanged.

**High soil burn severity**: All or nearly all of the pre-fire ground cover and surface organic matter (litter, duff, and fine roots) is generally consumed, and charring may be visible on larger roots. The prevailing color of the site is often "black" due to extensive charring. Bare soil or ash is exposed and susceptible to erosion, and aggregate structure may be less stable. White or gray ash (up to several centimeters in depth) indicates that considerable ground cover or fuels were consumed. Sometimes very large tree roots (> 3 inches or 8 cm diameter) are entirely burned extending from a charred stump hole. Soil is often gray, orange, or reddish at the ground surface where large fuels were concentrated and consumed.

## *Soil Characteristics*

Common changes to the soil include:

- loss of effective ground cover due to consumption of litter and duff;
- surface color change due to char, ash cover, or soil oxidation;
- loss of soil structure due to consumption of soil organic matter;
- consumption of fine roots in the surface soil horizon; and
- formation of water repellent layers that reduce infiltration.

The loss of effective ground cover is the single most important change that can greatly increase erosion and runoff. It is important to compare pre-fire ground cover to post-fire ground cover to understand how much has changed as a result of the fire. For example, if ground cover was sparse prior to the fire, soil burn severity should not be considered high as there was not enough fuel to maintain long duration heat to affect the soil to that degree.

The mineral soil color can also reflect the soil burn severity. In low soil burn severity, exposed mineral soil may appear brown or black. High soil burn severity soil can be orange or reddish due to soil oxidation or, more commonly, will appear grey due to ash cover or an ash/soil mix at the surface.

Soil structure can change by fire through the loss of structural aggregate stability. This is due to organic material combustion in the surface soil horizon. The combusted organic compounds act as an adhesive that bind soil particles into stable aggregates that resist detachment. Depending on the soil type and the degree of heating, exposed soils may become powdery, single-grained, or loose after intense heating and are highly susceptible to detachment by wind, water, and gravity.

Root condition can also be used to interpret soil heating severity. Fine root loss or charred larger roots in the surface soil horizon is the result of high heat for a sufficient duration.

Ash color and depth are indicative of soil heating. A thick layer (~3 inches or 8 cm) of powdery gray or white ash usually results from complete combustion of litter, duff, and surface fuels and can indicate severe heating. For reference, it takes approximately 8 inches (22 cm) of duff (assuming a bulk density of 0.1 g/cubic cm) to produce 1 inch (2.5 cm) of ash. However, ash may not always be a reliable indicator because it is highly mobile by wind and water.

### Water Repellency

Increasing burn severity is often incorrectly assumed to be positively correlated with increasing soil water repellency (Lewis and others 2006). However, pre-fire soil texture and type, amount and depth of litter cover, soil moisture, and soil organic matter as well as the temperature and residence time of the fire all affect the degree of soil modification and resulting soil water repellency (DeBano 2000a; Doerr and others 2000). Coarse-grained soils are more prone to fire-induced water repellency than fine-grained soils. Volcanic ash-cap soils, which are fine-grained, are usually naturally water repellent, but the degree of water repellency is often altered by fire heating (Robichaud and Hungerford 2000; Doerr and others 2000). Naturally water repellent soils are also frequently (but not always) found under canopies of true fir (*Abies* spp.) and under individual sage (*Artemisia* spp.) or chaparral shrubs (*Ceonothus* spp. and others). As the litter and duff on the soil surface is consumed in a fire, water repellent conditions are often created or exacerbated through the formation of hydrophobic compounds. However, very high temperatures (> 280 °C) or a long heating time may preclude the formation of water repellent soil at the surface. A water repellent layer may still be formed in the cooler subsurface that will hinder infiltration and increase runoff and erosion (DeBano 2000b). A thin layer of water repellent soil at or near the surface is common and will generally dissipate more quickly via bioturbation, gravity, and freeze-thaw cycles than will a water repellent layer deeper in the soil profile (Doerr and others 2000). Because the temperature and duration of forest fires and soil properties have high spatial variability, the connection between burn severity and soil water repellency is neither universally consistent nor well defined (Doerr and others 2000). See Appendix C for information on how to measure water repellency (Robichaud and others 2008a).

All of these factors should be considered together while determining the soil burn severity classification. Not all possible indicators must be present, but generally, two or more factors of high severity dominating an area may justify a classification of high soil burn severity for that polygon.

The following photo series exemplifies the soil burn severity descriptions provided above and includes:

A. Ground Cover: Amount and Condition
B. Ash Color and Depth
C. Soil Structure
D. Roots
E. Soil Water Repellency

# Soil Conditions Photo Series

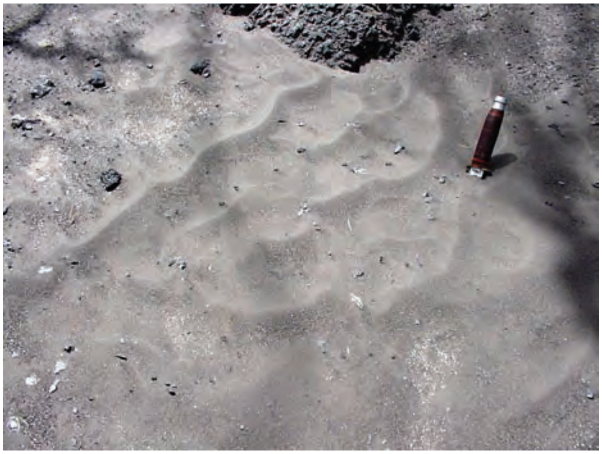
## *A. Ground Cover: Amount and Condition*

| | |
|---|---|
|  | **Low soil burn severity**<br>Little or no change from pre-fire status. Less than 50% consumption of litter, some char. Needles and leaves mostly intact. |
|  | **Moderate soil burn severity**<br>Up to 80% consumption of litter and duff, but generally incomplete. Recognizable leaves and needles remain. If more complete consumption occurred, a mitigating factor may be potential for leaf- or needle-cast from scorched canopy to provide ground cover. |
|  | **High soil burn severity**<br>Little to no effective ground cover remaining after fire (less than 20%). All or most litter and duff has been consumed, only ash or bare soil (ash blown away) remain. Little to no potential for leaf- or needle-cast. |

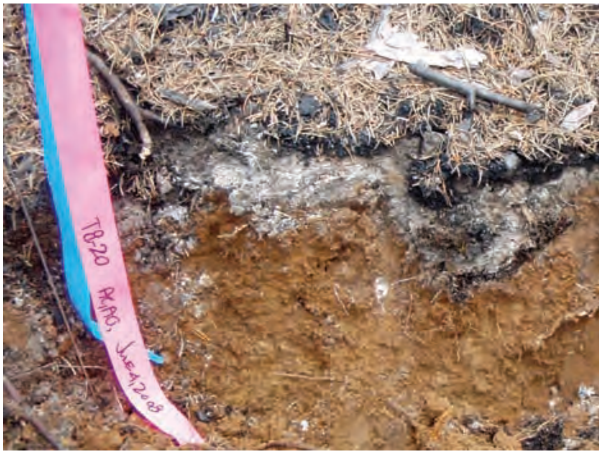
## B. Ash Color and Depth

| | |
|---|---|
|  | **Low soil burn severity**<br>Ground surface may be black with recognizable fine fuels (needles, grass, and leaves) remaining on surface. |
|  | **Moderate soil burn severity**<br>Thin layer of black to gray ash with recognizeable litter beneath it. Ash layer may be patchy as it is highly moveable by wind and water. Soil heating may have been significant; residence time usually brief. If thicker ash layer is observed, a mitigating factor may be leaf- or needle-cast potential from scorched canopy. |
|  | **High soil burn severity**<br>Thick, 1- to 3-inch (3- to 6-cm or more) layer of powdery gray or white ash covers the ground. Greater than 90% surface organics consumed; significant soil heating has occurred; residence time long. No potential for leaf- or needle-cast to provide ground cover.<br>Localized red (oxidized) soil may underlie a thick, powdery layer of gray and white ash–generally found near a burned out stump or log; indicates extreme heating. |

## *C. Soil Structure*

| | |
|---|---|
|  | **Low soil burn severity**<br>Structure unchanged. Granular aggregates are not weakened by consumption of organic matter. |
|  | **Moderate soil burn severity**<br>Structure slightly or not altered. Some consumption of organic matter in the top 0.5 inch (1 cm) of the soil profile. |
|  | **High soil burn severity**<br>Structural aggregate stability reduced or destroyed. Loose- and single-grained soil dominates and is exposed or under ash (up to 4 inches or 10 cm of ash). Consumption of organic matter in the top 2 inches (5 cm) of the soil profile. |

## D. Roots

| | |
|---|---|
|  | **Low soil burn severity**<br>Fine roots (~0.1 inches or 0.25 cm diameter) intact and unchanged. |
|  | **Moderate soil burn severity**<br>Fine roots near surface may be charred or scorched; large roots intact (~0.25 inches or 0.5 cm diameter). |
|  | **High soil burn severity**<br>Many or most fine roots near surface consumed or charred. Some charring may occur on very large roots (~3 inches or 8 cm diameter). |

## E. Soil Water Repellency

| | |
|---|---|
|  | **Low soil burn severity**<br>No fire-induced water repellency. Water infiltrates immediately; however, some soils exhibit water repellency even when unburned (see section 4.3). |
|  | **Moderate soil burn severity**<br>Weak to medium water repellency found at or just below soil surface. Water infiltrates slowly. |
|  | **High soil burn severity**<br>Strong water repellency found at surface or deeper. Water does not infiltrate. In case of extreme soil heating, soil water repellency may be destroyed or may exist at very deep soil depths (6 inches or 15 cm). |

# Pre-Fire Vegetation Considerations

Pre-fire vegetation density (including ground fuels, litter, and duff) is a key factor to consider when mapping soil burn severity. For the purposes of this field guide, vegetation types have been generalized into two pre-fire vegetation densities within three fire-prone ecosystems that represent widespread conditions in the western United States.

**Chaparral:** Low and high density chaparral vegetation are represented by chaparral or mixed shrub-chaparral vegetation communities. Ground fuels are characteristically sparse, except directly under the shrub canopy, with a range of low to high density canopy fuels. Mean annual precipitation generally ranges from 12 to 20 inches (30 to 50 cm).

**Mixed conifer forest:** The mixed confer forest contains ground fuels that range from sparse to dense. Mean annual precipitation varies widely from 20 to 80 inches (50 to 200 cm) and is generally dependent on elevation; higher elevation precipitation is dominated by snow. Sparse, dry ground fuels are characteristic of lower precipitation regimes; while higher precipitation regimes produce thicker, wetter, and denser ground fuels. Canopy fuels also vary largely by precipitation and locally by aspect (for example, south facing slopes are generally dry and sparse). Ground and canopy fuels may also vary if a recent disturbance such as disease, insect, or blowdown event has caused widespread tree mortality, or if a past disturbance such as thinning or harvesting occurred.

**Sagebrush/grassland:** The sagebrush/grassland has sparse ground fuels because of the arid climate associated with rangelands. Mean annual precipitation ranges from 4 to 8 inches (10 to 20 cm). Canopy fuels can be dense but are more often intermixed with patches of grass, native and non-native forbs, and exposed mineral soil. Though some of these areas are generally not at high risk of increased soil erosion after wildfires, they are often at high risk of weed or noxious species invasion and may be considered for post-fire rehabilitation treatments.

Beyond identifying the general vegetation density characteristics of an area, the spatial structure or heterogeneity/homogeneity of the vegetation must be considered. Large patches of dense vegetation (such as a hillside) in an otherwise sparsely vegetated area can lead to an area of high soil burn severity that may have hydrological implications in the event of high intensity precipitation. Smaller patches of dense vegetation that create high soil burn severity typically have less potential for increasing runoff or soil erosion in a watershed. Vegetation's spatial distribution affects fire behavior and residence time, which directly impact subsequent soil changes. Vegetation types and the spatial distribution of ground, surface, ladder, and canopy fuels can vary greatly across an area.

Pre-fire vegetation type and density are important factors to consider when interpreting the BARC layer. Before a wildfire, areas of low surface vegetation biomass will have low near-infrared reflectance values in remote sensing imagery. When a wildfire occurs and burns areas of low biomass, the change is not substantial to the satellite sensor and is often correctly classified as low soil burn severity in the BARC. This may be an appropriate classification when assessing only the soil and ground conditions. However, if the BARC (and its source data, the dNBR) is used to help map vegetation effects, it may underestimate the vegetative burn severity.

The following photo series is intended as a general guide. Choose the density model that most closely matches your site, and consider the severity indicators for that model. Be aware of localized discrepancies and their potential implications on the post-fire soil and ground conditions. Field specialist interpretation of soil conditions in areas of moderate vegetation density is necessary.

The following vegetation considerations photo series is arranged by density, vegetation class, and burn severity. See table 1 for a depiction of the likelihood of encountering these soil burn severity conditions.

# Vegetation Considerations Photo Series

## *A. Low Density Chaparral*

**Low soil burn severity, low density chaparral**—most common condition as ground and canopy fuels are sparse, causing minimal soil heating.

| | |
|---|---|
|  | **Substrate—<br>soil/litter/duff**<br>Surface litter charred or partially consumed. Leaf structures charred but recognizable. Mineral soil visible with discrete patches of ash; soil structure and roots unchanged. |
|  | **Surface vegetation—<br>understory/shrubs/forbs**<br>Fine fuels (grasses and forbs) scorched or partially consumed. Coarser shrub stems intact. |
|  | **Canopy vegetation—<br>ancillary factors for additional clues**<br>Canopy foliage mostly unaltered. Patches of scorched leaves generally not dominant.<br>5-30% charred canopy |

**Moderate soil burn severity, low density chaparral**—unlikely to occur as mappable polygons due to low vegetation density. These conditions may occur directly beneath individual shrubs.

| | |
|---|---|
|  | **Substrate—**<br>**soil/litter/duff**<br>Surface litter mostly charred or consumed; blackened or gray ash on surface. Soil structure and roots unlikely to be significantly altered. |
|  | **Surface vegetation—**<br>**understory/shrubs/forbs**<br>Finer fuels (grasses, forbs, and small stems) mostly consumed. Shrub stems charred; root crowns intact. |
|  | **Canopy vegetation—**<br>**ancillary factors for additional clues**<br>Canopy foliage mostly consumed; shrub skeletons and smaller stems (< 0.5 inches or 1 cm) remain.<br>30-100% charred canopy |

## B. High Density Chaparral

**Low soil burn severity, high density chaparral**—even in high density chaparral, soil heating is commonly of short duration, causing minimal effects on the soil.

| | |
|---|---|
|  | **Substrate—<br>soil/litter/duff**<br>Surface litter charred or partially consumed. Leaf structures charred but recognizable. Mineral soil visible with discrete patches of ash. Soil structure and roots unchanged. |
|  | **Surface vegetation—<br>understory/shrubs/forbs**<br>Fine fuels (grasses and forbs) scorched or partially consumed; shrub stems intact. |
|  | **Canopy vegetation—<br>ancillary factors for additional clues**<br>Canopy foliage mostly unaltered. Patches of scorched leaves generally not dominant.<br>5-30% charred canopy |

**Moderate soil burn severity, high density chaparral**—most common condition, canopy consumption may be patchy, mixed severity, or fairly continuous; soil moderately affected.

| | |
|---|---|
|  | **Substrate—<br>soil/litter/duff**<br><br>Surface litter mostly charred or consumed; blackened or gray ash on surface. Soil structure and roots unlikely to be altered. |
|  | **Surface vegetation—<br>understory/shrubs/forbs**<br><br>Finer fuels (grasses, forbs and small stems) mostly consumed. Shrub stems charred; root crowns intact. |
|  | **Canopy vegetation—<br>ancillary factors for additional clues**<br><br>Canopy foliage mostly consumed. Shrub skeletons and smaller stems (< 0.5 inches or 1 cm) remain.<br><br>30-100% charred canopy |

**High soil burn severity, high density chaparral**—generally found only in old, dense, decadent stands, especially if in large, continuous patches.

| | |
|---|---|
|  | **Substrate—soil/litter/duff**<br>All or most organic surface matter is consumed, leaving fine gray or white ash and extensive charred mineral soil. Soil surface black, brown, or reddish beneath ash. Fine roots and organic matter consumed, resulting in loss of soil structure. |
|  | **Surface vegetation—understory/shrubs/forbs**<br>Finer fuels (grasses, forbs, and small stems) consumed including fuels < 1 inch or 2 cm. |
|  | **Canopy vegetation—ancillary factors for additional clues**<br>Canopy foliage completely consumed. Only larger diameter (> 1 inch or 2 cm) stems remain.<br>90-100% charred canopy |

## *C. Low Density Mixed Conifer Forest*

**Low soil burn severity, low density forest**—most common condition as ground and canopy fuels are sparse, causing minimal soil heating.

| | |
|---|---|
|  | **Substrate—**<br>**soil/litter/duff**<br>Surface litter charred or partially consumed. Leaf or needle structures charred but recognizable. Duff largely intact. Soil structure and roots remain largely unchanged. |
| <br>2.8.2002 | **Surface vegetation—**<br>**understory/shrubs/forbs**<br>Finer fuels (grasses, forbs, and smaller shrubs) scorched or partially consumed. |
|  | **Canopy vegetation—**<br>**ancillary factors for additional clues**<br>Tree canopy mostly unaltered. Slight scorch may be observed.<br>5-10% charred tree canopy and < 3-ft or 1-m char heights |

**Moderate soil burn severity, low density mixed conifer forest**—unlikely to occur in very sparse forest systems except where significant understory occurs, and in those cases, soil burn severity is a function of the understory vegetation system rather than the sparse forest.

| | |
|---|---|
|  | **Substrate—<br>soil/litter/duff**<br>Surface litter charred or partially consumed. Leaf or needle structures charred but recognizable. Duff largely intact. Soil structure and roots remain largely unchanged. |
|  | **Surface vegetation—<br>understory/shrubs/forbs**<br>Finer fuels (grasses, forbs, shrubs, twigs, and small limbs) mostly consumed. |
|  | **Canopy vegetation—<br>ancillary factors for additional clues**<br>Tree canopy mostly scorched or consumed. |

## *D. High Density Mixed Conifer Forest*

**Low soil burn severity, high density forest–**will generally occur where surface fuels are lightest.

| | |
|---|---|
|  | **Substrate—**<br>**soil/litter/duff**<br>Surface litter charred or partially consumed. Leaf or needle structures charred but recognizable. Duff largely intact. Soil structure and roots remains largely unchanged. |
|  | **Surface vegetation—**<br>**understory/shrubs/forbs**<br>Finer fuels (grasses, forbs, and smaller shrubs) scorched or partially consumed. Twigs and small limbs on ground may also be consumed. |
|  | **Canopy vegetation—**<br>**ancillary factors for additional clues**<br>Tree canopy mostly unaltered. Slight scorch may be observed.<br>5-10% charred tree canopy and<br>< 3-ft or 1-m char height |

**Moderate soil burn severity, high density mixed confer forest**—most common condition; often interspersed with localized patches of low and high soil burn severity. Soil is moderately affected.

| | |
|---|---|
|  | **Substrate—<br>soil/litter/duff**<br>Surface organics may be charred, but leaf or needle structure recognizable. If consumed, charred needles or leaves on trees will create mulch quickly. Gray or black ash or charred litter may cover much of surface; soil structure and roots generally intact. |
|  | **Surface vegetation—<br>understory/shrubs/forbs**<br>Surface fuels and understory vegetation may be consumed. All plant parts may be consumed including fuels > 1 inch or 2 cm. Large logs consumed or deeply charred. |
|  | **Canopy vegetation—<br>ancillary factors for additional clues**<br>Canopy foliage scorched but generally not completely consumed. Needles or leaves remain on trees (significant potential for needle-cast to provide mulch).<br>10-80% charred canopy and<br>3-6-ft or 1-2-m char height |

**High soil burn severity, high density mixed conifer forest**—most likely to occur where ground fuels were dense prior to the fire. Can also be found in localized patches by tree stumps or where large, downed logs burned; soil is severely affected.

| | |
|---|---|
|  | **Substrate—<br>soil/litter/duff**<br>All or most surface organics are removed, leaving fine gray or white ash and extensive charred mineral soil. Soil surface black, brown, or reddish beneath ash. Soil structure weakened due to consumption of fine roots and organics. Evidence of previously significant litter or surface fuels (deep ash; duff lines on trees and rocks). |
|  | **Surface vegetation—<br>understory/shrubs/forbs**<br>Surface fuels and understory vegetation consumed. All plant parts may be consumed, including fuels > 1 inch or 2 cm. Most tree stems are charred, and large logs are consumed or deeply charred. |
|  | **Canopy vegetation—<br>ancillary factors for additional clues**<br>Canopy foliage completely consumed. Few to no needles or leaves remaining on trees (little to no potential for needle-cast to provide mulch).<br>90-100% charred canopy and<br>> 6-12-ft or 2-4-m char height |

## *E. Low Density Sagebrush/Grassland*

**Low soil burn severity, low density sagebrush/grassland**—only common condition; areas of burned, partially burned, and unburned litter and vegetation.

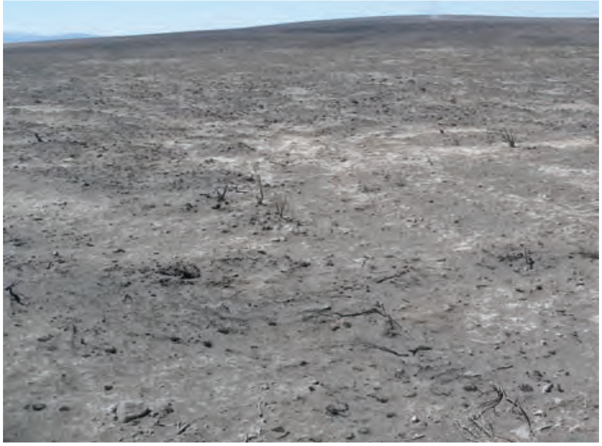
| | |
|---|---|
| <br>08/03/2007 | **Substrate—**<br>**soil/litter/duff**<br>Surface litter charred or partially consumed. Leaf structures charred but recognizable. Mineral soil visible with discrete patches of ash beneath individual shrubs. Soil structure and roots remain unchanged. |
|  | **Surface vegetation—**<br>**understory/shrubs/forbs**<br>Finer fuels (grasses, forbs, and smaller stems) scorched or partially consumed. Large shrub stems intact. |
|  | **Canopy vegetation—**<br>**ancillary factors for additional clues**<br>Patchy canopy foliage scorch; may be partially to almost completely consumed. |

## *F. High Density Sagebrush/Grassland*

**Low soil burn severity, high density sagebrush/grassland**—areas of burned and partially burned litter and vegetation.

| | |
|---|---|
|  | **Substrate—**<br>**soil/litter/duff**<br>Surface litter charred or partially consumed. Leaf structures charred but recognizable. Mineral soil visible with discrete patches of ash. Soil structure and roots unchanged. |
|  | **Surface vegetation—**<br>**understory/shrubs/forbs**<br>Finer fuels (grasses, forbs, and smaller stems) scorched or partially consumed; shrub skeletons and fine stems intact. |
|  | **Canopy vegetation—**<br>**ancillary factors for additional clues**<br>Canopy foliage scorched or partially consumed.<br>5-30% charred canopy |

**Moderate soil burn severity, high density sagebrush/grassland**—most common condition; may be patchy, mixed severity, or fairly continuous canopy consumed; soil not severely affected.

| | |
|---|---|
|  | **Substrate—<br>soil/litter/duff**<br>Surface litter mostly charred or consumed. Blackened ash on surface. Soil structure and roots unlikely to be altered. |
|  | **Surface vegetation—<br>understory/shrubs/forbs**<br>Finer fuels (grasses, forbs, and small stems) consumed. Sagebrush stems charred or consumed; root crowns intact. |
|  | **Canopy vegetation—<br>ancillary factors for additional clues**<br>Canopy foliage mostly consumed.<br>30-90% consumed canopy |

# Use of the Soil Burn Severity Map in Post-Fire Assessments

## Using the Soil Burn Severity Map

Once it is field verified, the soil burn severity map is combined with information about topography, pre-fire vegetation, and precipitation to determine the hydrologic and erosion response potential of burned watersheds. This is one of the most important purposes of the soil burn severity map. Hydrologic and erosion response predictions can be made with a variety of models and techniques. A brief summary of available models that are commonly used in the post-fire environment follows. The pros and cons of some of these models are discussed in detail by Foltz and others (2008). These model results can be displayed in tables, graphs, or GIS attribute layers.

## Common Post-Fire Hydrology and Erosion Prediction Models

**WEPP**: The Water Erosion Prediction Project (WEPP) is a physical-based model that predicts runoff, upland soil erosion, and hillslope sediment delivery (Flanagan and Livingston 1995). The climate file that drives WEPP is stochastically generated from 2600 historical weather station data and is modified by the Rock Clime interface for mountainous regions (Elliot 2004). Several interfaces have been developed specifically for post-fire assessments using the WEPP model. These and other erosion and runoff models used by BAER teams are discussed below. WEPP and its sub-models can be accessed online at http://forest.moscowfsl.wsu.edu/fswepp.

**ERMiT:** Erosion Risk Management Tool (ERMiT) is a tool developed specifically for post-fire assessments that predicts the probability associated with a given amount of single-storm soil erosion in tons/acre (tons/ha) for a given hillslope topography in each of five years following forest, chapparal, and sagebrush wildfires (Robichaud and others 2007). ERMiT also predicts the benefits of mitigation treatments during the recovery period for seeding, mulching, and installing contour-felled log erosion barriers.

**GeoWEPP:** GeoWEPP develops a drainage network for a selected region and then defines the channel network and hillslope polygons for a selected watershed by defining the watershed outlet for pre- and post-fire conditions (Renschler 2008). GeoWEPP utilizes two modes: “Flowpath” and “Watershed.” Flowpath mode predicts runoff and erosion for every pixel within the selected watershed. Watershed mode predicts sediment delivery from each hillslope polygon and stream channel segment identified.

**Disturbed WEPP:** Disturbed WEPP allows users to describe numerous disturbed forest and rangeland erosion conditions, including low and high soil burn severity conditions. The interface output provides mean annual runoff, erosion rates, and sediment yields as well as a return period analysis and the probability of a given amount of erosion occurring the year following a disturbance. Additionally, the user may review the WEPP summary and extended outputs.

**Curve Number:** The curve number (CN) method estimates runoff depth (Ponce and Hawkins 1996). It considers rainfall, soils, cover type, treatment/conservation practices, hydrologic conditions, and slope steepness. Users choose CNs based on cover type, treatment (in the case of post-fire modeling, soil burn severity), hydrologic conditions, and hydrologic soil group to estimate runoff and peak flow; therefore, the CN is the single most important parameter in this method. Two CN methods are often used during post-fire assessments: WILDCAT4 (Hawkins and Greenberg 1990) and FIRE HYDRO (Cerrelli 2005).

**TR-55:** The TR-55 model uses the runoff CN as an input parameter. The TR-55 is a simplified procedure to calculate the storm runoff volume, peak flow rate, hydrograph, and storage volume for storm water management structures in small watersheds (USDA NRCS 2005). It initially assumes a Natural Resource Conservation Service (NRCS) Type II rainfall distribution and later improves by adding three more rainfall distributions (Type I, IA, and III). TR-55 then programs the computations for estimating the time of concentration.

**WMS:** The Watershed Modeling System (WMS) (http://www.ems-i.com/index.html) provides a graphical interface to the TR-55 model and uses CNs to predict storm runoff, peak flow rate, and hydrograph for watersheds. The user can select the various rainfall distributions described under TR-55.

**RUSLE:** The Revised Universal Soil Loss Equation (RUSLE) model was developed for cropland applications to predict average annual erosion (RUSLE 1993). It has been applied to post-fire modeling using GIS techniques after the Cerro Grande Fire in New Mexico (Miller and others 2003) and with other fires.

**FERGI:** The Fire Enhanced Runoff and Gully Initiation (FERGI) model is a physical-based mathematical description of hillslope hydrologic and geomorphic response to a given set of weather events (Luce 2001). FERGI estimates the probability of post-fire rainfall excess, runoff generation amount, and gully initiation positions on hillslopes with and without mitigations using contour-felled logs or log erosion barriers.

**USGS Regression Equations:** The USGS regression equations are used to estimate magnitude and frequency of floods of both gauged and ungauged streams from watersheds greater than 5 $mi^2$ (13 $km^2$) (Thomas and others 1997). StreamStat, a web-based tool, has been used recently for various hydrologic regions based on their stream gauge records, basin characteristics, and numerous studies throughout the United States (USGS 2007). The pre-fire hydrologic response is adjusted based on the percentage of the watershed area that was burned at moderate and high soil burn severity and a user-defined modifier.

**Rational Method:** The traditional rational method was originally developed to calculate the flood peak flow under the assumption that the intensities of both rainfall and infiltration are uniformly distributed in time and space (Ponce 1989). The modified rational method adjusts the rainfall to a patterned or design storm distribution.

Model choice is often determined by the BAER team experience, available data, geographical area, and desired output. It is important to note that the soil burn severity map is not a map of runoff or erosion potential but it is an input into hydrologic or erosion models as it represents fire-caused changes in those parameters that affect runoff or erosion potential such as ground cover, hydraulic conductivity, hydrologic soil group, soil K-factor, curve number, and interrill/rill erodibility.

## *Displaying Surface Runoff Potential on Maps*

After the hydrologic models are run for the burned areas of interest, the results can be displayed in GIS. For example, a runoff potential map might represent the post-fire watershed response conditions that reflect the likely first-year runoff. These runoff amounts could be divided into four classes (unchanged, low, moderate, and high) that represent runoff or peak flow potential. The post-hydrology-modeling products generally do not produce what looks like a soil burn severity map because other physiographic features (slope, aspect, soil type, and expected precipitation) are used during the modeling.

### *Displaying Erosion Potential on Maps*

Using GIS, the soil burn severity map can be overlaid with slope, soil type, and amount of exposed soil and rock. These combinations can be grouped appropriately to aid in erosion modeling. For example, a series of ERMiT model runs for the dominant groups of characteristics can be calculated and the resulting values can be displayed in tabular form or added to the attribute table of the combined feature class to display a map of post-fire soil erosion potential. The erosion potential map may also look different from the soil burn severity map. A high soil burn severity condition on flat ground would have a low erosion potential due to the topography.

### *Other Uses of a Soil Burn Severity Map*

Additionally, the spatial and temporal "snapshot" of soil burn severity often becomes a baseline for monitoring changes in soil and ground conditions and vegetation recovery. Several other GIS products such as tree mortality can be derived from these maps and field observations. Overlaying the soil burn severity map with steep slopes or rock outcrops can be used for identifying and modeling post-fire slope stability issues. These maps can also be used to determine soil burn severity by ownership, watersheds, or land cover.

Analysis for implementation planning can be done using GIS to develop polygons of high soil burn severity that may be under consideration for treatment such as aerial seeding or mulching. Modeling can be used to determine natural reseeding likelihood based on polygon size and shape (edge effect) as well as to map the proximity of potential seeded areas to nest sites, cultural resources, and other resources at risk. In short, the soil burn severity map can be used by a variety of resource specialists for a range of analyses.

## Conclusion and Management Implications

Using a common set of soil burn severity indicators and definitions in rapid, post-fire assessment is important. The guidelines presented in this report will help users identify fire effects that are directly related to post-fire soil conditions rather than to overstory or ecosystem conditions. Consistency in assessments will lead to more credible products being used to evaluate post-fire risk to runoff and erosion potential and will lead to more informed and financially prudent decisions regarding post-fire rehabilitation treatments. The methods outlined in this report will also help increase the efficiency and speed of assessments and will allow specialists from different regions and disciplines to produce consistent products. The process of refining the BARC to create the soil burn severity map should be clearly documented with descriptions of all systematic and local adjustments to the soil burn severity classes. A few sentences and photos describing what low, moderate, and high soil burn severity looks like for each vegetation type is also an important part of the assessment record. These metadata and clearly labeled digital and hard copy BAER soil burn severity maps should be delivered to managers, other agencies, resource specialists, community groups, media, and individuals.

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# Appendix A—How to Map Soil Burn Severity

This *Field Guide for Mapping Soil Burn Severity* is intended to be a standardized guide to help users translate field-observed soil and site conditions that represent the low, moderate, and high soil burn severity classes into map polygons for use by resource specialists to predict runoff and erosion.

## *Mapping Concepts*

Mapping, whether done in GIS or by hand, is a skill that is generally tasked to an individual with expertise and knowledge of mapping concepts and, often, previous knowledge of the area being mapped. The following sources are excellent references for mapping, and, though focused on mapping soils, much of the information and many of the concepts apply to mapping natural resources in general. The National Soil Survey Handbook (USDA NRCS 2009) (http://soils.usda.gov/technical/handbook/*)* and Chapters 1 and 2 of the Soil Survey Manual (SSM) (Soil Survey Division Staff 1993) (http://soils.usda.gov/technical/manual/) are available online.

The discussion of soil forming factors in the SSM, Chapter 1, highlights the need for the mapper to understand the soil-landscape relationships in order to delineate polygons on a map:

> "Regional patterns of climate, vegetation, and parent material can be used to predict the kinds of soil in large areas. The local patterns of topography or relief, parent material, and time, and their relationships to vegetation and microclimate, can be used to predict the kinds of soil in small areas. Soil surveyors learn to use local features, especially topography and associated vegetation, as marks of unique combinations of all five factors. These features are used to predict boundaries of different kinds of soil and to predict some of the properties of the soil within those boundaries." (Soil Survey Division Staff 1993)."

Extending this idea of soil forming factors to soil burn severity, one could argue that soil burn severity is a function of pre-fire vegetation type, density, amount and type of ground fuels, litter, and terrain (as it influences fire behavior and fire frequency). Weather is the unpredictable element. We can directly observe these site factors (other than weather) or at least their post-fire evidence. An area with heavy ground fuels can experience high soil burn severity, whereas an area with little to no fuel will not. The heavy fuels provide the opportunity for high heat and long residence times—the main criteria resulting in high soil burn severity conditions. On the other hand, a fire can pass quickly over an area with light fuels such as grass. The vegetation may be consumed but heat residence time is brief and soil characteristics remain unchanged by the fire.

Post-fire field reconnaissance allows team members to examine the condition of the soil and to estimate the pre-fire characteristics at a given site. It is important for the mapper to be able to determine relationships between site characteristics and soil burn severity. For example, it is common to observe high soil burn severity in a California chaparral system on blackened, north-facing slopes that had high pre-fire vegetation density. Less dense (drier) south-facing slopes may also appear black after the fire but commonly exhibit moderate or low soil burn severity due to the lighter fuels. Observing and understanding this relationship can help to map, by extrapolation, those areas in large fires that an observer may not have time to visit.

Another element that is crucial to effective mapping is designing map units. Though this can be far more complex when mapping soils than when mapping soil burn severity, the basic concept is similar. Chapter 2 of the SSM provides useful insight:

> "While studying the soil patterns in different landscapes, the soil scientist must keep in mind how best to relate the patterns observed to

> appropriate map units. … This requires many judgments. Every map unit that is tentatively identified is evaluated by two tests: 1) Can it be mapped consistently? 2) Is it needed to meet the objectives of the survey?" (Soil Survey Division Staff 1993)."

To apply this to soil burn severity mapping, map units should be meaningful for the end use (predicting runoff and erosion) and not so complex or detailed that they cannot be mapped within the short time frame of a BAER assignment. Mappers can, in part, meet these goals by keeping the legend simple; using simple classes of "low," "moderate," "high," and "unburned"; and describing the map inclusions (or exclusions) in the map metadata.

This leads to the concepts of map unit purity, map scale, and delineation size. Chapter 2 of the SSM offers this guidance:

> "Standards of *purity* are adjusted according to the precision required by the survey objectives. Probably all delineations contain some kinds of soil besides that identified in the map unit name."
>
> "The *map scale* must be large enough to allow areas of minimum size to be delineated legibly. … The choice of map scale also depends on the perspective of the user."
>
> "Map users who want a broad perspective of large areas, however, are usually concerned with comparisons among delineations of all, or a large part, of the map. Consequently, delineations on maps for such uses are generally larger and fewer in number." (Soil Survey Division Staff 1993)."

With BAER soil burn severity mapping, the scale (and detail) of mapping is almost always more general. There is not sufficient time during a BAER assessment to create a highly detailed map of soil burn severity, nor would such a detailed map effectively meet the needs of the users (runoff and erosion prediction). The increased use of remote sensing and BARC maps has greatly increased both the level of detail and precision of soil burn severity mapping, and the digital nature of the BARC lends itself to use in spatial models for runoff and erosion. It is important to keep in mind, however, that the models used are not particularly sensitive to slight changes in soil burn severity; thus, it is more efficient and more useful to keep the map units (soil burn severity classes) and delineations fairly broad while still accurately capturing the location and distribution of soil burn severity classes in the watersheds throughout the burned area.

### *Points to Consider When Mapping Soil Burn Severity:*

The ultimate purpose of the soil burn severity map is to predict increased runoff and erosion from the burned area, especially in areas with resource values at risk. Remembering this will help users keep perspective on the level of detail and focus their efforts on specific areas at risk.

- *Get the big picture.* A quick reconnaissance (via helicopter, overlooks, or quick drive-throughs) helps to get an overview of the burned area and to develop a sense of the extent, location, and distribution of the "green," "brown," and "black" areas. These are the broad visual indicators that will guide the surveyor's field observations and map delineations. It is a good idea to record notes on a topographic map or post-fire satellite image of the area. To avoid bias, avoid using the BARC.
- *Gather field information.* As much time as possible should be spent on the ground gathering site-specific information. This field time can begin by visiting areas that were identified during the reconnaissance as largely "green," "brown," or "black." These become representative polygons for

each vegetation type and density. Detailed notes should be taken, data should be recorded on the field data sheet (Appendix B) at as many ground points and traverses as possible, and GPS coordinates should be collected for those points and traverses. The mapper can now begin to assess the types of vegetation, terrain, and other features in these areas and the ground conditions and can develop an understanding of the relationships among pre-fire vegetation, terrain, and soil burn severity.

- *Start forming "map unit" concepts.* For example, a large area appeared blackened from the air. During the field visit, it turns out that while it is all black, half of it was dense forest (pre-fire) and half of it was shrubland. Ground conditions in these areas indicate that the dense forested areas exhibit a preponderance of soil characteristics that point to a high soil burn severity classification (for example, deep ash, no fine fuels or soil cover remaining, loss of soil structure, etc). In the shrub areas, however, soil characteristics point to a moderate classification (for example, some unburned litter remains under the thin ash, structure is intact, etc). This is a relationship that can likely be extrapolated to other parts of the burn. There will not be time to visit every polygon, so the mapper must learn to develop these relationships in mind and take good notes.
- *Focus the majority of field time in the "black."* "Black" and sometimes "brown" areas are most likely to be sources of increased runoff. There will never be enough time to visit all of the identified at-risk field sites, so field time should be spent wisely. However, spending some time in the "green" will help the mapper understand what pre-fire soil and ground conditions looked like so a determination can be made as to how much has been changed as a result of the fire.
- *Develop a concept of purity.* Based on initial field investigations, it might be estimated that the black areas that were mapped as "high" soil burn severity in forest types are 80 percent high but have scattered inclusions of moderate and low. Or black, shrubby areas that were mapped as "moderate" are generally 75 percent moderate, but have small spots of "high" or larger spots of "low" scattered in them. Capture these concepts in field notes and map metadata. It is important to include these descriptions of soil burn severity classes in the mapping technical report.
- *Draw polygons on a map.* If available, a post-fire satellite image should be used; if not, a topographic map should be used. A post-fire satellite image helps determine exactly where likely polygon delineations should be drawn; however, cutoffs between categories are not always "black and brown," so to speak. Judgment calls based on field data and reconnaissance will be needed when drawing polygon boundaries. The end use of the map (runoff and erosion prediction) should be kept in mind as delineations (polygons) are created—meaning, areas that are likely to behave similarly should be lumped, and areas that will behave differently should be split.

All of the above steps are greatly facilitated if the mapper has a BARC that is a decent fit to the field ground observations. If the BARC is a good start but not accurate, determine whether systematic or localized edits are needed (see page 5).

# Appendix B—Soil Burn Severity Field Data Sheet and Key

| | | | |
|---|---|---|---|
| **Soil Burn Severity Assessment Field Data Sheet** | | **Fire name:** | **Observers:** |
| **Date:** | **Site ID:** | **GPS coordinates:** | **BARC classification:** |

| **Observation point** | **Ground cover (1)** | **Surface color and ash depth (2)** | **Soil structure (3)** | **Roots (4)** | **Soil water repellency (5)** | | | **Observed soil burn severity class (6)** | **Photo #** | **Other comments** |
|---|---|---|---|---|---|---|---|---|---|---|
| ***EXAMPLE*** | ***20 to 50%*** | ***white, 1 mm*** | ***no change*** | ***intact*** | ***I*** | ***3 mL*** | ***surf*** | ***Mod*** | ***23*** | ***homogenous*** |
| 1 | | | | | | | | | | |
| 2 | | | | | | | | | | |
| 3 | | | | | | | | | | |
| 4 | | | | | | | | | | |
| 5 | | | | | | | | | | |
| 6 | | | | | | | | | | |
| 7 | | | | | | | | | | |
| 8 | | | | | | | | | | |
| 9 | | | | | | | | | | |
| 10 | | | | | | | | | | |
| **Average/majority for site (7)** | | | | | | | | | | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Site characteristics:** | Aspect (deg): | | Slope %: | | | | |
| Slope length (ft or m): | Slope position: | Lower | Middle | Upper | Ridge | Other | |

| | | | | |
|---|---|---|---|---|
| **Soil texture class:**<br>clay loam, silt loam, loam | **Dominant pre-fire vegetation type** | **Pre-fire vegetation density** | **Vegetation comments:** | **Other notes:** |
| Surface rock %: | Chaparral | Low | | |
| **Soil comments:** | Forest | High | | |
| | Sagebrush/grassland | Other | | |
| | Other | | | |

This form is a guide for 10 observation points at a single field stop. It will not always be necessary to record 10 observations if site variability is low; however, if variability is high, more observations may be needed. The purpose is to quickly record information to document observations of soil burn severity and provide support and rationale for post-fire treatments. This form will also provide metadata to describe site conditions. The data collected here may be used as inputs to hydrologic models.

You will have to use your professional judgment when estimating change from pre-fire conditions. Examine areas of similar soil and vegetation that have not burned and form your opinion as to the degree it has or has not been changed by the fire. An electronic copy of this form is available at http://forest.moscowfsl.wsu.edu/BAERTOOLS/.

## *Data Form Columns:*

(1) **Ground cover**: Record an estimated percentage of cover (greater than 50%; 20 to 50%; or less than 20%). Ground cover means effective organic cover as it pertains to mitigation of runoff and erosion and includes litter, duff, and woody debris.

*Example: "20 to 50%"*

(2) **Surface color and ash depth**: Include a brief note on color and depth of ash (inches or cm), if any.

*Example: gray, 5 cm*

(3) **Soil structure**: Has it changed from pre-fire structure? The most common change is from a granular structure in the surface horizon to a loose- or single-grained soil in areas where heat residence time was long and organic matter was consumed.

*Example: "changed (loose)" or "no change"*

(4) **Roots**: Have they been altered from pre-fire condition?

*Example: "scorched," "no change," or "very fine consumed"*

(5) **Soil water repellency**: Use the infiltrometer (I) or water drop penetration time method (W) and record volume of infiltration or how long water takes to infiltrate, respectively. If repellency is observed, note the depth tested (inches or cm).

*Example: "I/3mL/at surface" or "W/25 sec/ at 1-2 cm"*

(6) **Observed Soil Burn Severity Class**: Record the soil burn severity class at the observation point.

*Example: "Unburned," "Low," "Moderate," or "High"*

(7) **Average/Majority for Site:** Estimate the most frequent or average of the 10 observations.

# Appendix C—Using a Mini-Disk Infiltrometer to Assess Post-Wildfire Soil Water Repellency and Reduced Infiltration

The Mini-disk Infiltrometer (MDI) has been adapted for use as a field test of post-fire infiltration and soil water repellency. Although the Water Drop Penetration Time (WDPT) test has been the common field test for soil water repellency, the MDI test takes less time, is less subjective, and provides a relative infiltration rate. The relative infiltration rate indicates reduced infiltration potential that may result from fire-induced soil water repellency, soil sealing, and other factors. For each test, the porous base plate of the MDI is placed on the soil, and the amount of water that passes into the soil in one minute is measured. Post-fire soil water repellency has most often been detected at 0.2 to 1 inch (0.5 to 3 cm) below the visible surface. In burned areas, soil surface measurements where soil and ash mix often indicate non-water repellent soil, making it necessary to brush or "dust" the ash away before testing the uppermost soil layer (fig. C1).

**Field test materials:**
- Mini-disk Infiltrometer
- water
- hand trowel
- stopwatch
- ruler to measure soil depth
- data recording sheets
- plastic squirt bottle for rinsing porous disk

**Test steps** *(abridged version, see Robichaud and others 2008a):*

(1) Using a brush or trowel (depending on testing depth), expose the soil to be tested by removing overlying material (ash and organic material).
(2) Fill the MDI and set to 1 cm suction.
(3) Record the start volume (mL).
(4) Place the MDI porous disk flat against the soil with the MDI held perpendicular to the surface. Start the timer when the MDI disk and soil come into contact.
(5) Continue to hold the MDI against the soil surface so that the entire infiltration disk is in contact with the soil for one minute.
(6) At the end of one minute, remove the MDI from the soil and record the end volume.

**Figure C1.** Using the MDI in the field.

## *Sampling a Burned Area*

Post-fire assessments of soil water repellency and reduced infiltration are needed within days of fire containment. This short time frame for sampling necessitates a sampling scheme that 1) focuses on areas where soil water repellency and reduced infiltration are most likely; and 2) provides a logical method for extrapolation of sample results to unsampled areas.

The burned area is divided into areas of similar characteristics based on the factors that correlate strongly with post-fire soil water repellency—burn severity and slope aspect (which is used as a simple surrogate for vegetation type and density). MDI tests are done along transects located on upper and lower positions of selected hillslopes from each combination of moderate and high burn severity and north and south aspects. The results from the sampled hillslopes are applied to other burned but not sampled hillslopes with the same burn severity and aspect. Like most statistical analyses, the more measurements taken, the higher the confidence level assigned to the results. This sampling scheme, based on the classification of the burned area, can provide practical guidance for making the most of the limited time available for post-fire assessment.

A recently published Research Note (RMRS-RN-33), *New Procedure for Sampling Infiltration to Assess Post-Fire Soil Water Repellency* (Robichaud and others 2008a), provides instructions for using the Mini-disk infiltrometer, field data sheets, a detailed sampling scheme with pre-determined sample size and confidence levels, and a formatted data analysis spreadsheet tool. An electronic copy of the Research Note and spreadsheet tool can be accessed at: http://forest.moscowfsl.wsu.edu/BAERTOOLS/.

## *Interpreting Results*

The MDI test measures the volume of water (mL) that passes from the infiltrometer into the soil in one minute. Through field testing, the one-minute interval has been proven to be long enough to detect water repellent soil conditions yet fast enough to be a useful assessment procedure for post-fire assessment teams. The MDI test provides a relative infiltration rate that can be used to classify soil water repellency and compare the infiltration capacities of tested sites. The mean of three individual MDI readings is the MDI value at that sample location. The MDI value determines the degree of soil water repellency (strong, weak, or none) at each depth sampled at each location. The proportion of MDI values (percent) that indicate strong, weak, and none are used to describe the degree and extent of soil water repellency on the assessed hillslope.

Three classes of soil water repellency were identified based on the relationship between the common WDPT test and MDI test values performed at the same location:

| **MDI test** | **WDPT test** |
|---|---|
| Strong (0 to < 3 mL min$^{-1}$) | WDPT values > 40 sec |
| Weak (3 to < 8 mL min$^{-1}$) | WDPT values of 11-40 sec |
| None (> 8 mL min$^{-1}$) | WDPT values of 0-10 sec |

The WDPT values listed above are from the guidelines generally followed by the BAER community. Because moderate water repellency is difficult to define and the implications for potential watershed response can be ambiguous, we suggest using strong, weak, and none for water repellency classes. Strong water repellency is indicative of significantly reduced infiltration and increased potential for watershed response. Areas with strong water repellent soils will often be targeted for post-fire erosion and runoff mitigation. Soils classified as weak (or none) generally have an infiltration potential similar to the pre-fire condition.

The soil water repellency data collected with this sampling scheme is specific to a class of soil burn severity and slope aspect (moderate/north, moderate/south, high/north, or high/south), and the assessment from the sampled slopes is applied to the unsampled slopes of the same soil burn severity and aspect. This can be useful in prioritizing areas for post-fire stabilization treatments. Other factors to consider when prescribing stabilization treatments are: 1) fallen needle cover (needle-cast) that may provide substantial natural protection from erosion; and 2) the size of patches (continuity) of severely burned areas because large patches can also increase runoff and erosion potential even if soils were not classified as strongly water repellent.

# Appendix D—Example of the Soil Burn Severity Mapping Process, 2006 Derby Fire

The Derby Fire (45.6° N., 109.9° W) burned approximately 200,000 acres (81,000 ha) on the Gallatin National Forest in Montana. The fire burned a variety of vegetation types (grass, shrub, and forest) and over substantial elevation changes (3900 to 7400 ft or 1200 to 2250 m). The fire began on 22 August 2006 and burned until 15 October 2006. Due to the size of the fire and the long burning period, the use of remote sensing benefited the BAER team as it made its rapid assessment.

The following figures show the pre- and post-fire imagery (figs. D1 and D2), the BARC layer (fig. D3), and the field-adjusted final soil burn severity map created by the BAER team (fig. D4).

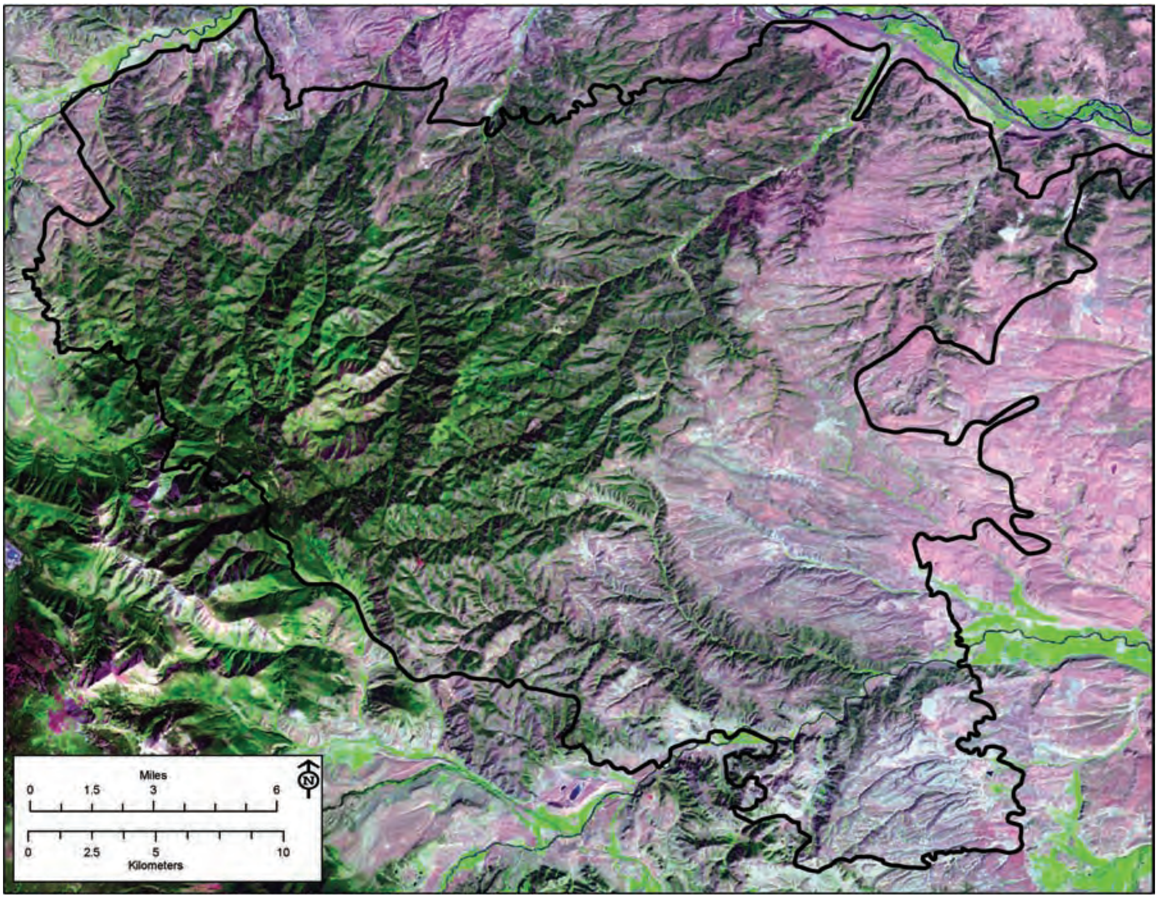

**Figure D1.** Pre-fire Landsat imagery of the Derby Fire acquired 2 September 2003. The fire perimeter is the black outline.

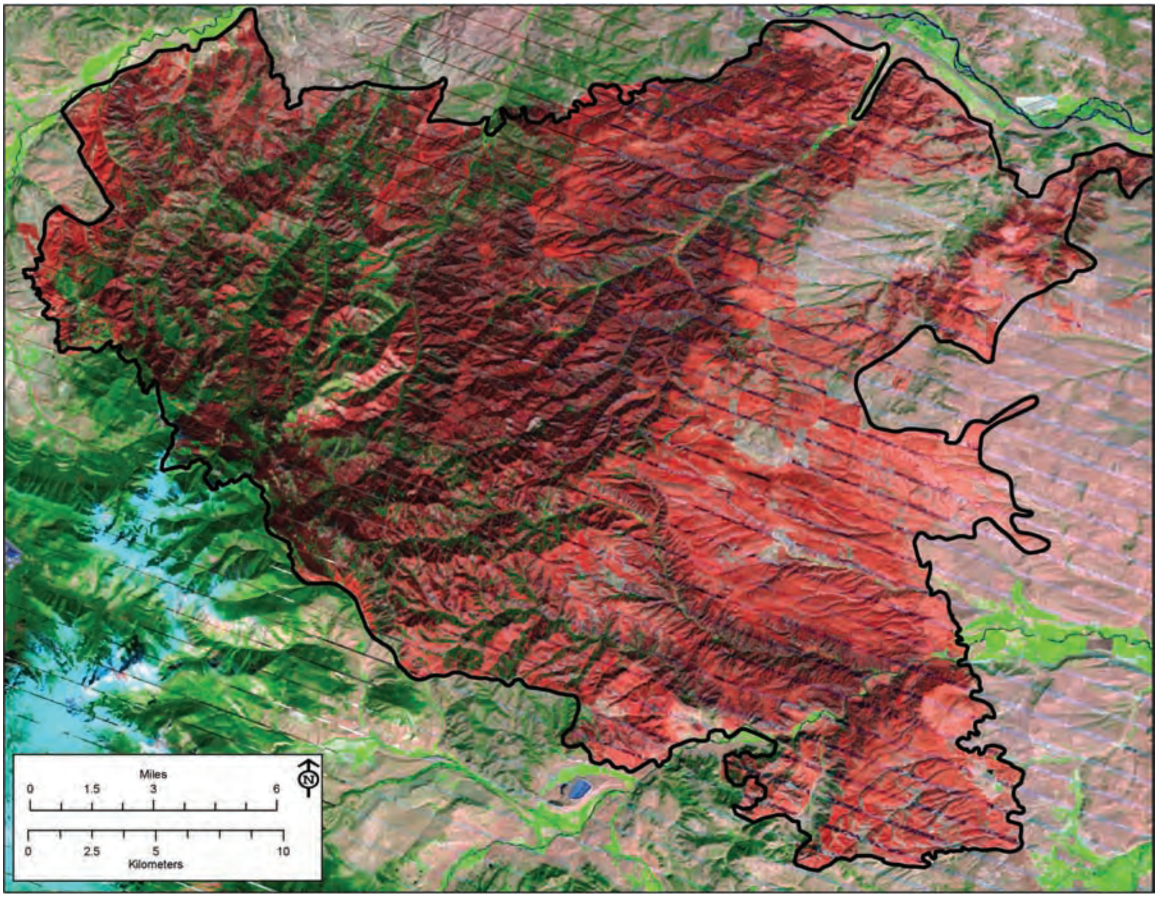

**Figure D2.** Post-fire Landsat imagery of the Derby Fire acquired 18 September 2006. The fire perimeter is the black outline.

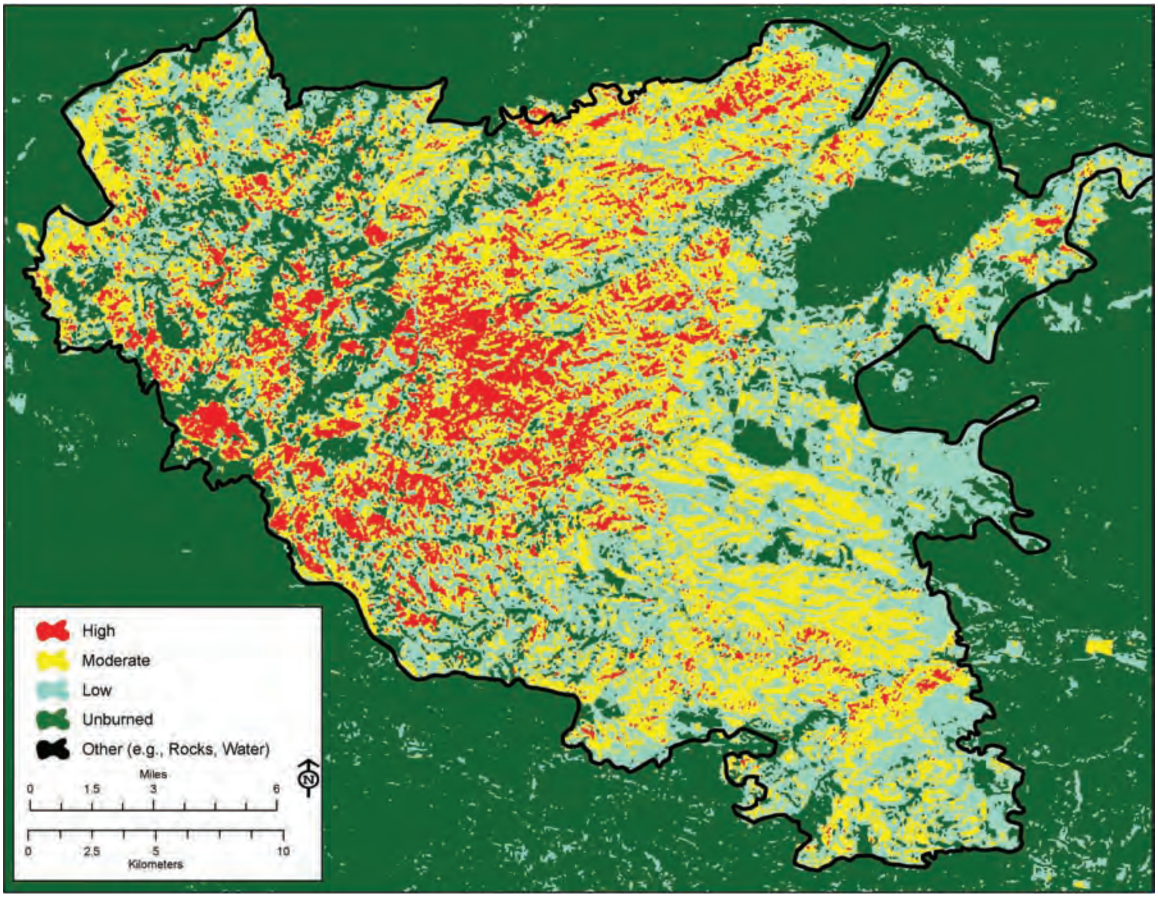

**Figure D3.** Initial BARC map of the Derby Fire. Preliminary BARC thresholds were 0-75 (unburned / very low); 76-130 (low); 131-187 (moderate); and 188-255 (high). The fire perimeter is the black outline.

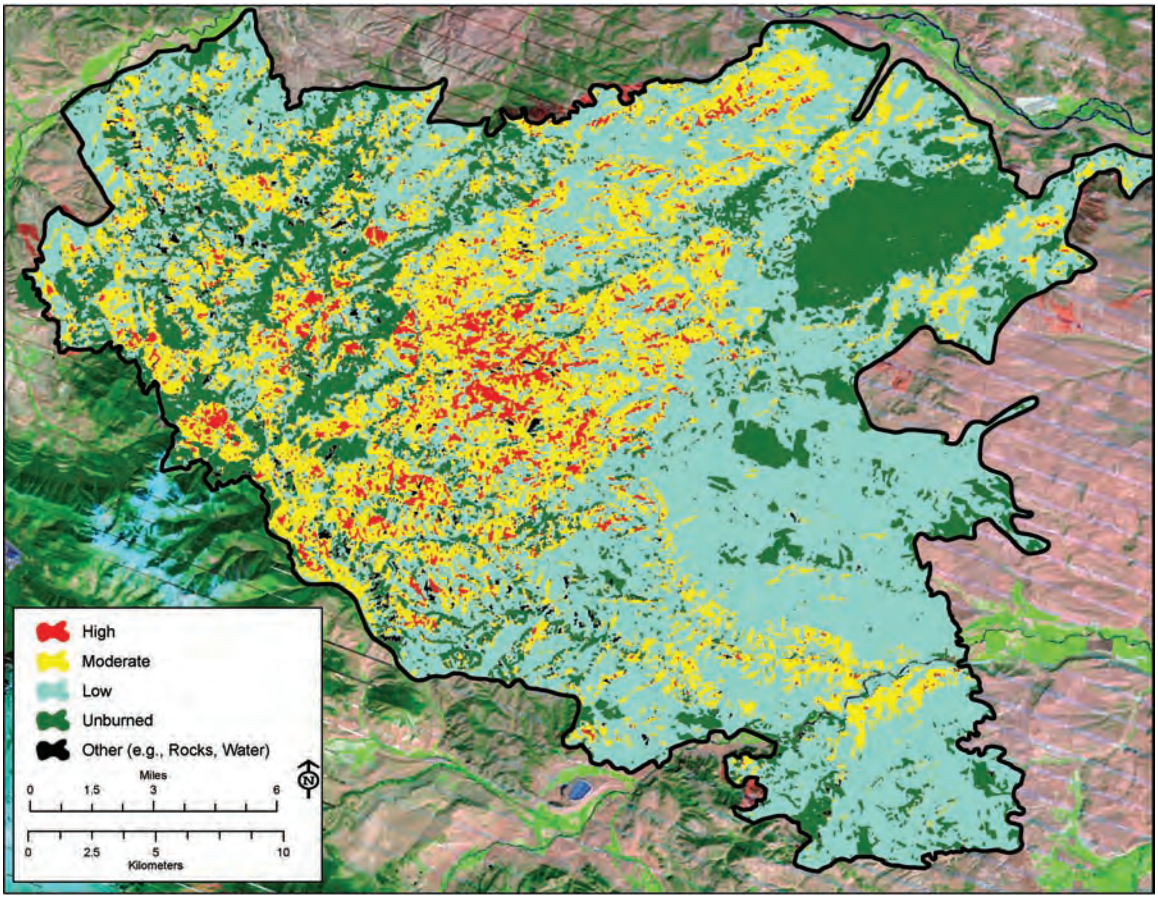

**Figure D4.** Final field-adjusted soil burn severity map of the Derby Fire. In order to achieve an acceptable classified image, the BAER team had to separate the forest lands from the grasslands and classify each vegetation type separately. The field observations indicated that the BARC overestimated high and moderate soil burn severity. Final BARC thresholds used by the BAER team were 0-75 (unburned/very low); 76-160 (low); 161-214 (moderate); and 215-255 (high). The final severity map shows smaller patches of both high and moderate severity while increasing the low severity. The BAER team clipped the soil burn severity layer to the fire perimeter.

# Appendix E—Summary of Soil Burn Severity Class Factors

### Adapted from the BAER Handbook (USDA 1995) by Alex Janicki.

| Factor considered | Soil burn severity class | | |
|---|---|---|---|
| | **Low** | **Moderate** | **High** |
| **Aerial view of canopy** | Tree canopy largely unaltered.<br>Shrub canopy intact and patches of scorched leaves not dominant. Ash is spotty. | Tree canopy is scorched over 50% of area. Shrubs mostly charred but difficult to assess fuels from air. Black ash is visually dominant. Gray or white ash may be spotty. | Tree canopy is largely consumed over > 50% of area. Shrubs completely charred but difficult to assess fuels from air. Gray and white ash is visually dominant. |
| **Vegetation**<br>Trees | Nearly all of crown remains “green.” Some scorching in understory trees. | High scorch height. Generally, > 50% of crown is scorched. Mostly “brown” crowns with intact needles. | No needles or leaves remaining. Some or many branches may be consumed. Mostly “black” remaining vegetation. |
| Shrubs | Scorching in canopy but leaves remain mostly green. Limited fire runs with higher scorch. 5 to 30% charred canopy. | 30 to 100% charred canopy. Smaller branches < 0.5 inch (1 cm) remain. Shrub density was moderate or high. | 90 to 100% charred canopy. Most branches consumed, including fuels < 1 inch (2.5 cm). Skeletons or root crowns remain. Shrub density was moderate or high. Often old growth in character. |
| Fine fuels (Grassland) | Scorched or partially consumed. | Mostly consumed. Appears black from the air. Small roots and seed bank remain intact and viable. | Not rated as high unless loss of seed bank is suspected or soil structure strongly altered. |
| **Ground cover** | Generally, > 50% litter cover remains under trees—less under shrub community or where pre-fire cover is sparse. | Generally, 20 to 50% cover remains or will be contributed by scorched leaf fall from trees. Shrub litter will be mostly consumed. | 0 to 20% cover remains as burned litter and woody debris under trees. Shrub litter is consumed. |
| **Water repellency** | Soils may be naturally water repellent under unburned chaparral. Other soils will infiltrate water drops in less than 10 sec; greater than 8 mL min$^{-1}$ with the MDI. | The surface of the mineral soil below the ash layer may be moderately water repellent but water will infiltrate within 10 to 40 sec; 3 to 8 mL min$^{-1}$ with the MDI. | Strongly water repellent soils (repels water drops for > 40 seconds; less than 3 mL min$^{-1}$ with the MDI) may be present at surface or deeper. |
| **Soil** | Original soil structure—fine roots and pores are unaltered. | Original soil structure—roots and pores slightly altered or unaltered. Soil color darkened or charred at surface or just below surface only. | Soil structure to 1 inch is degraded to powdery, single-grained, or loose. Fine roots are charred. Pores are destroyed. Black charred soil color common below thick ash layer. Compare with unburned. |

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