2022 Portugal Wildfires

Burned Area Emergency Response (BAER) Review

Photo 1. Vale de Amoreira in the Serra da Estrela burned area. (USFS photo)

The US Agency for International Development-Bureau for Humanitarian Assistance (USAID-BHA) and the US Forest Service (USFS) deeply appreciate the warm hospitality of the Institute for Nature Conservation and Forestry (ICNF) during the team's visit to the 2022 wildfires. We value the dedication of the ICNF staff and the opportunity to have technical exchanges related to post-fire assessment and treatments. This open and collaborative relationship allowed for a successful mission to aid future post-fire response in Portugal. In particular, the USFS team would like to acknowledge Nuno Sequeira, João Pinho, Jorge Dias, Rita Novais, Inês Vasco, João Moreira, Elmano Silva, Hugo Rocha, Rafael Neiva, Cláudia Salgueiro, Miguel Gonçalves, Carlos Loureiro, João Loureiro, Bruno Duarte, Carlos Esteves de Sá Ramalho, João Ribeiro, and Luis Pita for their support in coordinating the field visits and supplying technical data and services. They contributed invaluable insight on the country and its resources and provided outstanding logistical support throughout the mission. We also thank the ICNF Board for their support of this mission.

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Overview

This report summarizes a rapid characterization of post-fire conditions for eight 2022 wildfires prioritized by the ICNF. We discuss the threats and risks to critical values associated with the burned areas and offer some recommendations on best approaches to burned area response for these fires, as well as on future wildfires. Several burned areas were assessed in three regions—Serra da Estrela (one fire), Murça (two fires), and Leiria (five fires)—from 17 to 27 October 2022. The focus of this report is the land and communities within and downstream of the fire perimeters that may be at risk of damage or loss due to conditions of the burned areas. Critical values considered in this report include human life and safety and critical transportation infrastructure. Threats that exist or are amplified in the post-fire setting include accelerated soil erosion and runoff that results in increased sediment transport, higher stream flows, floods or debris flow, landslides, and rock fall.

The goal of this evaluation was to identify emergency conditions for critical values that are found to be at unacceptable risk from imminent post-fire threats, and to recommend general response actions to reduce the risk and mitigate post-fire impacts to critical values. There has already been a tremendous amount of work completed by local authorities within the fire areas, including burned area assessments, hillslope and channel treatments, and recovery work on roadways, among others.

The Burned Area Emergency Response (BAER) Process

Burned area emergency assessments are rapid evaluations conducted to determine if critical values are at risk due to imminent post-fire threats and to develop appropriate actions to manage unacceptable risks. The BAER team assesses the fire's effects to the landscape and predicts the potential post-fire consequences focusing on life and safety and critical transportation infrastructure. These assessments are not intended to provide a comprehensive evaluation of all fire or suppression damages, nor to identify long-term rehabilitation or restoration needs.

The first step in a burned area assessment is to identify values that are potentially at risk from post-fire events. Once the critical values have been identified, each value should be assessed for potential threats from post-fire conditions. To then characterize post-fire threats, the BAER team takes field observations of soil and watershed conditions to estimate anticipated levels of erosion, flooding, and debris flows.

The interdisciplinary BAER team evaluates each critical value and threat combination using a risk matrix considering both the probability of damage or loss and the magnitude of the consequences (Figure 1). A post-fire emergency is identified as a critical value found to be at unacceptable risk of damage due to post-fire conditions. Unacceptable risk is defined as very high or high risk in the United States, using the matrix. In addition to focusing the assessment team to the areas of highest concern, the risk determination can be used to prioritize implementation of mitigation measures.

After defining the post-fire emergency, a response strategy that considers natural recovery is developed to mitigate the risk. The assessment team identifies the threat or emergency type, location, duration, and extent prior to determining appropriate emergency treatments. For USFS BAER, response actions need to be 1) proven effective, 2) the minimum action needed to reduce the risk to an acceptable level, 3) economically justified, and 4) possible to implement prior to damaging events. Actions are short-term or temporary measures that generally do not require maintenance or can be discontinued after objectives have been met.

Probability of Damage or Loss	Magnitude of Consequences		
	Major	Moderate	Minor
	RISK		
Very Likely	**Very High**	**Very High**	**Low**
Likely	**Very High**	**High**	**Low**
Possible	**High**	**Intermediate**	**Low**
Unlikely	**Intermediate**	**Low**	**Very Low**

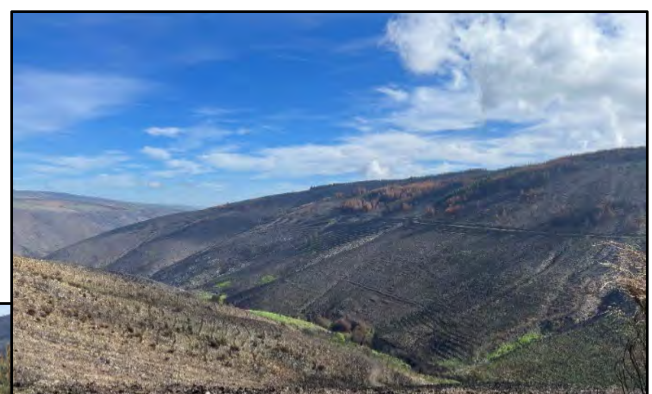
Probability of Damage or Loss: The following descriptions provide a framework to estimate the relative probability that damage or loss would occur within 1 to 3 years (depending on the resource):

- Very likely. Nearly certain occurrence (90% - 100%))
- Likely. Likely occurrence (50% - 89%)
- Possible. Possible occurrence (10% - 49%)
- Unlikely. Unlikely occurrence (0% - 9%)

Magnitude of Consequences:

- Major. Loss of life or injury to humans; substantial property damage; irreversible damage to critical natural or cultural resources.
- Moderate. Injury or illness to humans; moderate property damage; damage to critical natural or cultural resources resulting in considerable or long term effects.
- Minor. Property damage is limited in economic value and/or to few investments; damage to critical natural or cultural resources resulting in minimal, recoverable or localized effects.

Figure 1. USFS BAER Risk matrix used to determine emergency treatment needs.



Photos 2, 3, and 4. Evidence of landscape alteration with both new and historic terracing and stream channelization within the Serra da Estrela burned area. (USFS photos)

Field Review and Analysis

The Serra da Estrela fire started in early July 2022 and was contained in early September, having burned about 27,340 hectares (67,559 acres). The Murça (7,156 hectares [17,682 acres]) and Revel fires (1,638 hectares [4,048 acres]) burned for short periods in mid to late July 2022 and ultimately combined into a single burned area. Five separate fires that burned from mid-July to mid-August combined to form the burned area assessed in the Leiria region (9,192 hectares [22,713 acres]).

Landscape History

Like much of Europe, land use in the 2022 burned areas has changed greatly over the years, having shifted from upland agriculture to forest and shrubland. Much of the landscape within the fire perimeters has been heavily impacted by past management and land-use alterations. Historic management actions resulted in deforestation and overgrazing leading to severe erosion and loss of landscape productivity. Recognition of the negative impacts of these management actions led to the establishment of the ICNF and Serra da Estrela Natural Park. To address past flooding and erosion, many erosion mitigation measures were installed, including rock check-dams in many of the headwater drainages and larger structures in the lower valley bottoms (Photos 2-6). In addition, the lower hillslopes were terraced to support small-scale agriculture and the streams channelized for irrigation and water management. Some of these terraces are still used for agricultural production, but many have been abandoned. Also, many of the streams have been diverted into confined tunnels underneath roadways within villages. In recent years, some upper slopes have also been terraced for reforestation efforts, agricultural tree products, and timber production. These landscape alterations complicate efforts to predict post-fire watershed response using common wildland analytical approaches.

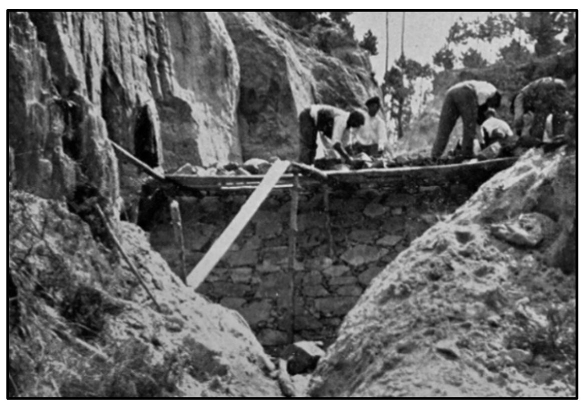
Photos 5 and 6. Evidence of landscape alteration with terracing on the Murça and Revel fires. (USFS photos)

Soils and Geology

Various geologies were observed in the burned areas. The Serra da Estrela mountains are an uplifted granite massif intermixed with sedimentary and metamorphic base rock. The western and central part of the fire is underlain by schist and graywacke while the eastern portion of the fire is dominated by granite. The fires in the Murça area are underlain by quartzites, schist, greywacke, and granites. The schist and greywacke formations are prone to mass soil-movement events. The Leiria burned areas are underlain by two distinct formations, one consisting of limestone, dolomite, and marl and the second of sandstone and conglomerate. Several large, historic erosional features were found in the sandstone areas (Photo 7). In these and similar areas across Portugal, ICNF had placed mitigations in the valley bottoms in the early to mid-20th century to help mitigate erosion and flooding concerns (Photos 8 and 9).

Photo 7. Evidence of historic erosion within the Leiria burned areas (USFS photos).

The soils within burned areas consist primarily of leptosols, cambisols, luvisols, and regosols as described in the World Reference Base for Soil Resources (WRB). Leptosols are very shallow soils over hard rock or deeper soils that are extremely gravelly and/or stony. Cambisols are soils in the beginning of soil formation with weak horizon development. Luvisol soils are of mixed mineralogy with high nutrient content and good drainage. Regosols are very weakly developed mineral soils in unconsolidated materials. Regosols are extensive in eroding lands, particularly in arid and semi-arid areas and in mountain regions. All of the soils observed within the burned areas had a very high percent of surface rock fragments (50-100%) with large boulder fields throughout much of the eastern portion of the Serra da Estrela fire. The soils of the Serra da Estrela area had sandy and sandy loam surfaces while the soils in the Murça and Leiria fires were generally of a finer texture.



Photos 8 and 9. Historic erosion mitigations. (Photos provided by ICNF)

Steep slopes were observed in the Serra da Estrela and Murça fire areas, typically ranging from roughly 15° to 30°+ (27 to 60%+) slope. The Leiria fires were typically gentle slopes, generally less than 15° (~27%) slope. Also, field observations found a general absence of large, downed wood due to past timber harvest removal.

Soil Burn Severity

As noted above, one of the first steps that USFS BAER teams complete is an assessment of the *soil* burn severity. Over the years, scientists have learned that impacts to the soil (versus impacts to vegetation) is the most important indicator of potential post-fire watershed impacts and recovery (Figure 2). From the soil burn severity map, geologists can predict debris flow hazards, hydrologists can predict changes to runoff and flood flows, and soil scientists can predict erosion potential.

While soil burn severity exerts the most influence on post-fire watershed response, the above-ground vegetation burn severity does influence hydrologic processes and can inform the recovery of a burned forest. For example, in areas where conifer trees are scorched and killed but the canopy was not consumed, the needles will fall soon after the fire and provide ground cover to mitigate rainfall impact and runoff (Photos 10 and 11).

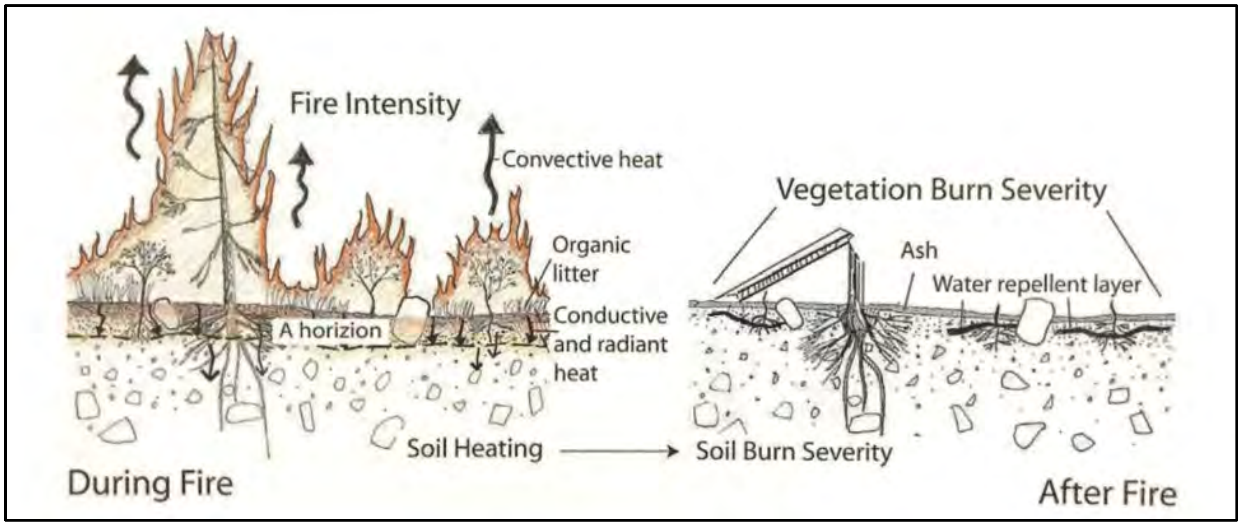


Figure 2. Diagram depicting differences in soil burn severity and vegetation mortality.

Photo 10 and 11. Pictures showing low soil burn severity with needle cast from Pinus pinaster. (USFS photos)

The final soil burn severity maps were developed in ESRI ArcGIS using satellite-imagery-derived Burned Area Reflectance Classification (BARC) and field survey data (~185 field data points) (Table 1 and Figures 3-5). Field work to document and confirm soil burn severity was completed between 10/18/22 - 10/26/22. Field work included assessment of ash characteristics, ground cover, roots, soil structure, soil water-repellency, and vegetation burn intensity. Field assessment sites were focused in areas of high and moderate burn severity, especially in drainages above critical values such as villages. No high soil burn severity was identified during the field survey, including in areas with high vegetation mortality. Field data were used to adjust the BARC map to produce the final soil burn severity information.

Table 1. Final hectares in soil burn severity classes for the burned areas.

Soil burn severity class	**Serra da Estrela**	**Murça**	**Leiria**
Unburned/Very Low	3,363 ha (8,309 ac)	300 ha (742 ac)	307 ha (759 ac)
Low	13,857 ha (34,242 ac)	7,037 ha (17,388 ac)	8660 ha (21,399 ac)
Moderate	8,992 ha (22,219 ac)	1,813 ha (4,479 ac)	88 ha (218 ac)
High	None	None	None

The soil burn severity determinations were made without the presence of an ash layer since validation work was completed after several rainstorms had washed the ash layer from most hillslopes. While the ash layer is an important characteristic used to help determine soil burn severity as described in the *Field Guide for Mapping Post-fire Soil Burn Severity*, soil burn severity can still be determined using the remaining indicators. In addition, hydrophobicity was not used as a key characteristic during the soil burn severity mapping. Strong hydrophobicity was found both within and outside of the burned area in unburned conditions. This background hydrophobicity is partly a function of the vegetation but is also likely exacerbated by the extreme drought of the past year.

Photo 12. ICNF's Hugo Rocha examining fire effects to fine roots in a low soil burn severity stand outside of Lousã. (USFS photo)

Low soil burn severity was classified in areas where the surface organic horizons were charred but primarily intact with very fine and fine roots still pliable (Photo 12). Vegetation recovery is anticipated to be rapid in these areas and was already observed in many locations (Photos 13 and 14). In addition, since there was ground cover remaining, post-fire erosion will be mediated in these areas naturally.


Photos 13 and 14. Early vegetation growth observed in low soil burn severity areas. (USFS photos)

Moderate soil burn severity was found in areas where the organic horizons were completely consumed by the fire with very fine and fine roots charred and brittle (Photos 15). No surface organic matter remained in these areas resulting in an anticipated increase in post-fire erosion concerns. Areas in the fire that had extensive surface rock exposed by the fire were most likely reflected in the BARC as potential high soil burn severity (Photo 16). Soils in these areas experienced at most moderate soil burn severity and are reflected as such in the final soil burn severity maps.


Photos 15 and 16. Examples of moderate soil burn severity mapped in the Serra da Estrela fire. (USFS photos)

Field observations suggested a high potential for needle cast and litter accumulation in pine and eucalyptus forested areas of the burned areas within low and moderate soil burn severity areas. Furthermore, robust vegetative response was observed, including resprouting of bracken fern, oak and eucalyptus trees, native scotch broom, and other shrubs in low and moderate soil burn severity. The most consistent changes in soil conditions occurred in moderate soil burn severity, resulting in charred and brittle very fine to fine roots and increased sub-surface hydrophobicity. Additionally, where shrubs dominated the hillslopes, very little to no canopy remained; these areas are likely more susceptible to post-fire erosion with potential impacts to long-term soil productivity (Photos 17 and 18).

Photos 17 and 18. Burned shrub-dominated hillslopes mapped as moderate soil burn severity. (USFS photos)

While no areas of high soil burn severity were observed during the field review, the following information is provided to help identify these areas in future events. High soil burn severity is characterized by a complete consumption of the organic material with the surface layers of the soil resulting in a change in structure to single grain and color of the soil surface becomes orange (Photo 19). This is often found in areas of reburns where there is a high concentration of heavy fuels on the ground that resulted in a long duration heat impact to the soil (Photo 20).

Photos 19 and 20. High soil burn severity observed on the 2022 Cedar Creek Fire in Oregon, USA. (USFS photos)

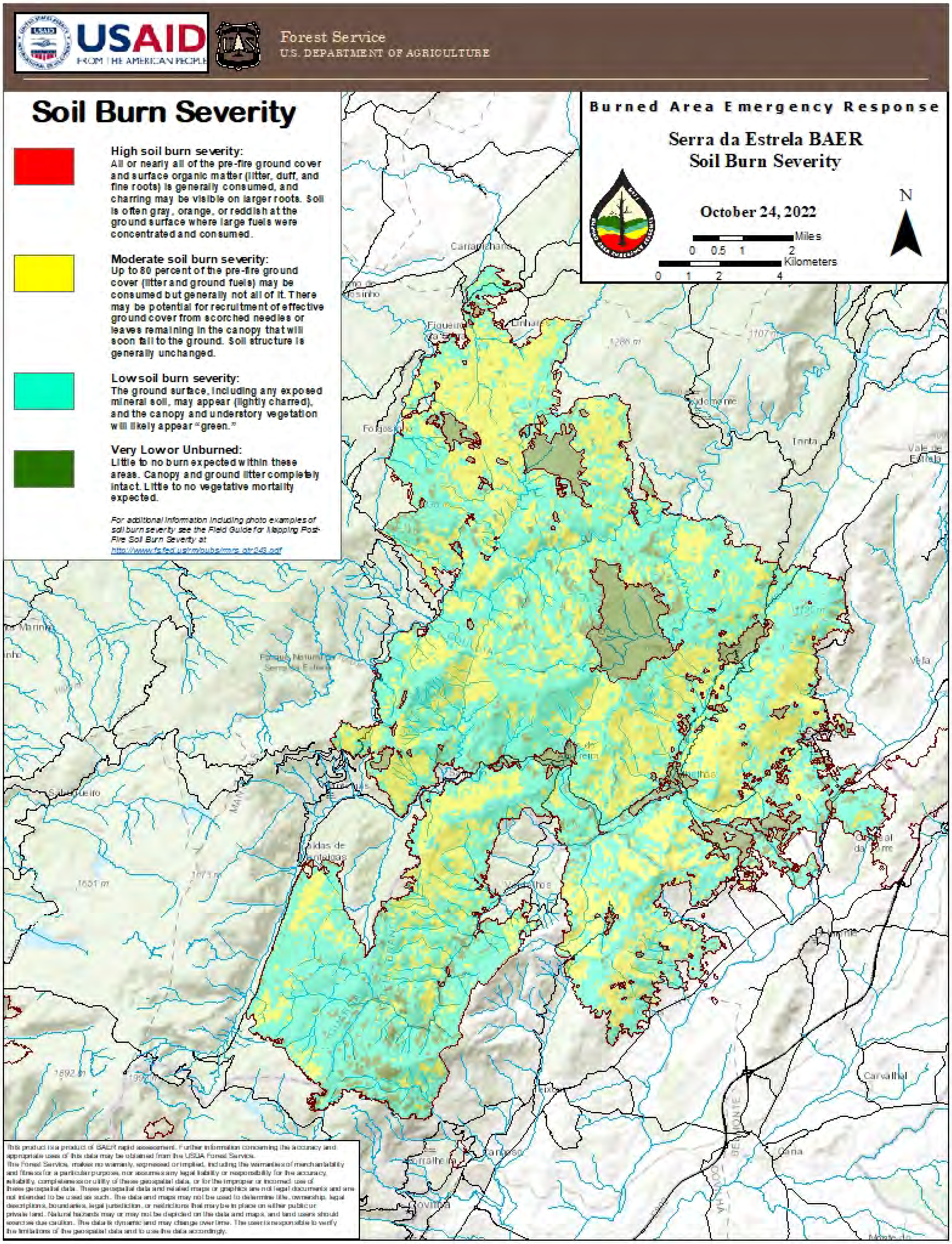


Figure 3. Serra da Estrela soil burn severity map.

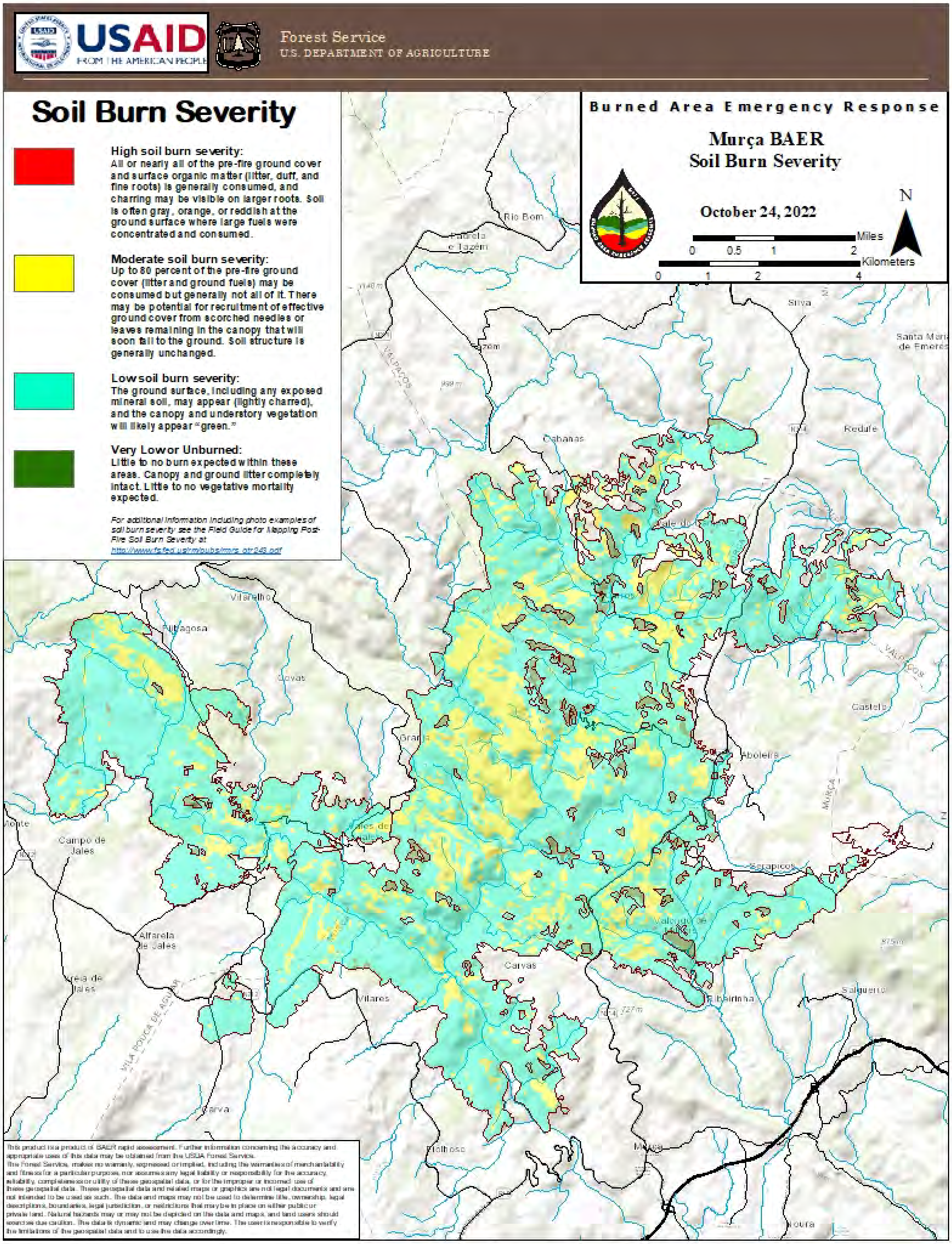


Figure 4. Murça fires soil burn severity map.

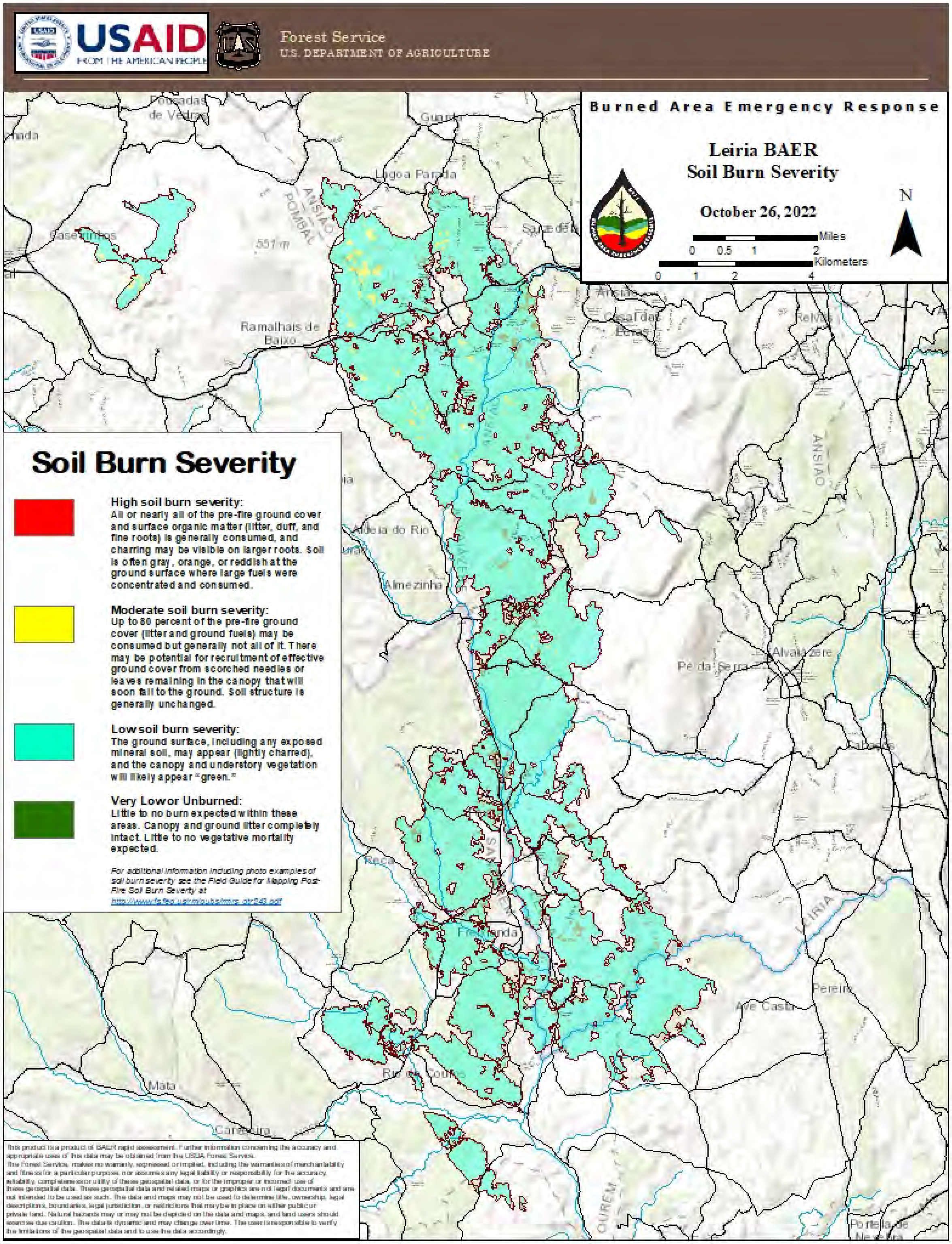


Figure 5. Leiria fires soil burn severity map.

Soil Erosion Modeling and Analysis

It is well understood that fire-damaged soils are at higher risk for erosion and increased surface runoff. This is due to several factors including loss of overstory and litter cover for the mineral soil, changes in soil structure, and increased hydrophobicity. While the soil burn severity mapping shows most of the burned areas in low and moderate classes, it is still anticipated that the level of erosion will increase over pre-fire conditions (Photos 21 and 22). The US team did model post-fire erosion on a subset of the areas of concern for the fires using standard USFS processes and Appendix A includes more detailed information on the modeling approach, variables, and interpretation of results. Both the standard USFS processes and Portugal's post-fire soil erosion risk assessment (Parente et al. 2022) show anticipated increases in erosion across these landscapes in the post-fire environment. It is difficult to compare the results as the USFS models predicted increases of erosion from 30-118 MG/ha on modeled hillslopes, while the post-fire soil erosion risk assessment map produced by Parente et al. lumps all erosion greater than 10 MG/ha into the highest category. Regardless of model technique, those landscapes that are naturally prone to erosion and debris flows, such as the headwaters above Sameiro and Vale de Amoreira and the sandstone areas in the Leiria burned areas, will likely see increased erosion, runoff and debris flows in both the low and moderate soil burn severity areas. In addition, if historic erosion features are reactivated during post-fire events, there could be severe consequences to downstream infrastructure.

Photos 21 and 22. Observed erosion in low soil burn severity areas in the Serra da Estrela and Murça fires. (USFS photos)

Soil Disturbance from Post-Fire Management

Post-fire management such as salvage logging, site preparation for reforestation, and associated practices could exasperate and increase anticipated erosion and runoff events (Photo 23). These practices further disturb burned soils and remove organic material from the surface. Using best management practices to mitigate the additional disturbance is common practice in the US. For example, skid trails are minimized to only those necessary for efficient removal of merchantable material and logging slash is left on site to help provide ground cover. Current regulations in Portugal do not allow for leaving logging slash on site in timber operations due to fire danger concerns. While we understand this regulation in a pre-fire setting, the lack of post-fire ground cover after a salvage operation, in addition to the ground disturbance creating during the harvest, will likely lead to an increased level of erosion and soil productivity loss.

Photo 23. Salvage logging operation observed within the Murça burned area. (USFS photo)

Hole planting and contour rip-plowing planting are mechanical site preparation techniques that are widely used in reforestation programs in the Mediterranean basin. Stands within the Murça fire areas were observed where rip-plowing had occurred after the last wildfire during reforestation efforts. Recent research in Portugal has found that these techniques along with post-fire salvage logging greatly increase erosion when used in the post-fire setting (de Figueiredo et al. 2011, Lopes et al. 2020, Malvar et al. 2014, Prats et al. 2014). Using best management practices to help mitigate erosion should be considered when using these practices.

Geologic threats: debris flows, slumping, and rockfall

Debris flows (also called mudslides) are fast-moving flows of mud and rock and are among the most numerous and dangerous types of landslides in the world. They are particularly dangerous to life and property because they move quickly, destroy objects in their paths, and often strike with little advanced warning. Wildfire typically alters the hydrologic response of a watershed such that even modest rainfall amounts can produce debris flows (USGS Debris Flow Fact Sheet). Debris flows are commonly initiated in steep headwater slopes or from roads. Recent and historical debris flows have occurred within the burn areas. Evidence of past debris flows indicates a present risk of post-fire debris flows. Both recent

Photos 24, 25, and 26. Evidence of recent and historic debris flows in the valley above Sameiro in the Serra da Estrela fire, near Mascanho in the Murça fire, and near Freixianda in the Leiria fires. (USFS photos) and historic debris flows were observed in the headwaters above Sameiro and Vale de Amoreira in the Serra da Estrela fire, in the Mascanho and Valongo de Milhais areas in the Murça fires, and in the sandstone geologies of the Leiria fires (Photos 24-26). The sediment and wood in debris flows also add volume to downstream flood waters, which can form obstructions at constriction points such as culverts and bridges, or locations where streams are routed underneath village streets. These debris dams often lead to water ponding and flooding behind the blockage, and potentially causing a subsequent flood wave downstream if the debris dam fails catastrophically, releasing the impounded waters and debris.

Slumps are masses of rock or material that slide in a more-or-less coherent mass on a curved plane. These events are typically not large and do not travel far or fast. Slumps commonly occur because the base of the slope has been over-steepened, for example due to the construction of a cut-and-fill road or by flattening areas for housing. Slumps commonly slide onto road surfaces and can cause road failures. Poorly cemented sedimentary formations, such as alluvial deposits or loosely cemented clastic deposits, are more likely to slump. Fires can exacerbate slumping activity, especially along terraces, roads, trails, and other infrastructure corridors where slopes have been modified, by increasing water runoff. Slumped material can also be reworked by water, increasing debris loads to streams and water-management infrastructure. There was hillslope slumping noted above the new housing on the southwest portion of Curros within the Murça fires. This area should be monitored for increased soil movement due to post-fire effects.

Rockfall is a type of rapid landslide where rocks or particles of rocks fall down steep to vertical slopes. Generally, rockfall is composed of one to a few rocks; more than that and it is considered a rockslide or debris avalanche. Rockfall typically originates from hard, erosion-resistant rock that becomes unstable for a variety of reasons. Rockfall events can cause property loss, personal injury, or even loss of life. Rockfalls can also create unexpected hazards on roads, causing damage to vehicles. Rockfall was noted along the major highways accessing the fires and had already been mitigated with rockfall fencing. The increase in rockfall post-fire should not exceed the capability of current mitigations. However, if new areas with increased rockfall are noted after post-fire events, additional mitigations such as warning signs for life and safety of motorists may need to be installed.

Hydrology

Post-fire hydrology analysis methods

Typical US Forest Service BAER hydrology analytical methods include a field assessment to identify critical values vulnerable to flood and related damage, an estimation of post-fire hydrologic response to rain events, and evaluation of potential mitigation measures to reduce risk of damage to critical values. Prior to the field assessment, the burned area is reviewed using maps and aerial imagery (frequently in Google Earth), ideally including the initial Burned Area Reflectance Coverage (BARC) data. Buildings, transportation infrastructure (e.g. roads, culverts, bridges), water developments, and camping areas adjacent to streams within and below the burned area are identified and prioritized for field assessment. In the field, these critical values are examined to determine their vulnerability to damage from post-fire flooding. The field survey typically includes qualitative assessments, as well as quantitative data collection where modeling is warranted.

Following the field assessment, post-fire runoff estimation is typically completed for areas of particular concern. A range of models and techniques are used to estimate post-fire runoff and erosion. Each approach has its advantages and shortcomings, but any estimation of post-fire watershed response is imprecise at best. BAER teams thus generally avoid reporting stream runoff estimates as specific flow values, but instead report the estimated magnitude of change in runoff response between pre- and post-fire conditions. These estimates assist in determining where measures can be taken to reduce the risk of damage to critical values from flooding and erosion. An example of USFS BAER hydrologic modeling was completed for the watershed draining to the village of Sameiro and summarized in Appendix B.

Observations from the burned areas

Critical values observed within and below the fire perimeters that are potentially vulnerable to post-fire flooding and related events include life and safety in several villages located along streams, developed areas on floodplains, as well as road infrastructure and agricultural areas throughout the area. Although the soil burn severity was generally found to be low or moderate across the burned area, the reduction of groundcover and canopy have led to large increases in runoff response following relatively common rainfall events. A storm on the night of September 12-13 produced about 67 mm of rain in 12 hours at the Lagoa Comprida meteorological station, roughly eight miles southwest of the Ribeira do Vale do Sameiro watershed, and likely produced a similar or greater precipitation amount over the watershed. The rainfall measured at the Lagoa Comprida station appears to be roughly equivalent to a two-year (50% occurrence probability) storm for this general area (Brandão et al., 2001). The well-publicized flooding that occurred in the village of Sameiro as a result of this storm was likely exacerbated by the combination of wood debris and artificial flow restrictions on the main channel (under a building) as well as on a tributary that flows into a confined tunnel underneath a section of road (Photo 27).

Photo 27. Ribeira do Vale do Sameiro in the center of the village. (USFS Photo)

A useful contrast to this rain event were the rains that fell during mid-to-late October 2022. While precipitation data were not available for these storms at the time this report was written, the rainfall generally fell at a lower intensity over a longer duration, lasting several days. The more gradual input of water to the burned watersheds generally resulted in more modest stage increases throughout most of the burned area. Also, the loss of ash from the landscape during the September storms generally resulted in reduced impairment of water quality in area streams from the October storms, although increased turbidity was noted.

Threats to critical values in or below the Murça fires were limited to potential damage to the transportation system throughout the burned area, loss of reservoir capacity at Praia Fluvial De Penabeice and Praia Fluvial de Curros, damage to multiple irrigation diversion intake structures on Rio de Curros, and erosion and sedimentation in agricultural fields and terraces.

Within the Leiria burned area, increased post-fire runoff is expected to damage the transportation system as well as enlarge existing gullies within the burned area (Photo 28). Multiple buildings and roads were observed adjacent to existing gullies. Further erosion and gully enlargement could result in catastrophic damage to adjacent infrastructure if stabilization measures are not taken.

Photo 28. Existing gully in a salvage logging unit, adjacent to homes in the Leiria burned area. (USFS Photo)

Watershed response

Streams in the burned areas generally drain steep, dissected terrain. Many hillslopes in the burned watersheds have been modified through historic management practices, including extensive terracing to support agriculture and forestry as well as rock check dams across headwater channels (Photo 29). Road density within the burned areas is also quite high, which can increase watershed responsiveness to rain input. Baseflows in larger streams in the burned areas tend to be relatively low, with flashy, storm-driven peaks. Although annual precipitation in the burned areas follows a pattern typical of Mediterranean climates, the high-intensity, shorter-duration rainstorms most likely to trigger post-fire floods and debris flows generally occur during summer months. Higher elevations within the burned areas frequently accumulate snow during the winter, though snowpack does not typically persist for more than a few weeks.

Photo 29. Typical hillslope terracing within the Serra da Estrela burned area. (USFS Photo)

Post-fire conditions will reduce runoff response time and increase peak flows through reduced infiltration and more efficient overland flow, as well as sediment bulking. The latter process will be especially pronounced in steeper headwater drainages, where sediment concentrations in floodwaters are more likely to transition to hyper-concentrated flows and debris flows. Higher-intensity rain events have already triggered sediment and debris-laden floods and debris flows in the headwaters as well as sediment-laden flood flows in larger basins, most notably in the village of Sameiro on September 12-13, 2022. Culvert obstruction and road failure from sediment and debris has already occurred and is expected to continue following relatively modest rainstorms in smaller headwater basins, and in larger streams during flooding from lower-probability storms (Photo 30).

Photo 30. Stream crossing damage on an ephemeral channel caused by culvert plugging and overtopping. (USFS photo)

Watershed response will gradually return to pre-fire conditions as vegetation recovers and any fire-induced soil hydrophobicity is reduced to naturally occurring background levels. Brush, forbs, ferns, and grass species have already resprouted across much of the burned areas. Needle cast from scorched pines has occurred and will continue through the coming months. As vegetation and groundcover become re-established, infiltration rates and surface roughness will approach pre-fire conditions and watershed response will gradually return to pre-fire conditions, likely within three to five years.

Water quality

Recent studies of the effects of wildfire on municipal water supply have identified increases in nitrates, phosphorous, dissolved organic carbon (DOC), turbidity, total suspended solids, and metals in streams draining areas affected by wildfire (Hohner et al., 2019; Emelko et al., 2011; Rhoades et al., 2011, 2018; Writer et al., 2012). The effects of a wildfire on source-water quality can be long-lasting. In the Rocky Mountains of Alberta, post-fire water quality degradation persisted throughout a ten-year analysis period following the fire (Emelko et al., 2011). Chow et al. (2019) found elevated levels of elevated DOC and other disinfection byproduct (DBP) precursors in streams 14 years after the Hayman fire in Colorado. However, Pierson et al. (2019) found that carbon and nitrogen yields were highest in burned-area streams in the first two years post-fire at several western U.S. fire locations and diminished substantially in subsequent years. Additionally, elevated sediment, debris and nutrient deposition in reservoirs can reduce reservoir capacity, impact diversion structures, and diminish water quality.

Although the team did not have access to detailed location data for municipal source waters and infrastructure, most diversions providing drinking water to villages in the vicinity of the burned areas appeared to be upstream of burned areas or otherwise unlikely to be substantially impacted by post-fire water quality concerns. Municipal water system operators in these headwater areas are encouraged to evaluate all diversions and evaluate which, if any, may divert degraded water during rainstorms. If possible, these diversions can be closed prior to larger rain events. Water quality and municipal diversions for larger cities that are located a considerable distance downstream from the burned areas are unlikely to experience major impacts. These diversions are located at points in the river network that drain large watersheds, most of which were not burned in the 2022 fires. Thus, water quality impacts from the burned areas will be diluted and impacts minimal. Nonetheless, downstream municipal and agricultural diversion operators should plan for the potential of degraded water quality during larger rain events over the next few years.

Post-fire Vegetation Mapping Products – Comparison and Use

The USFS's *Rapid Assessment of Vegetation Condition After Wildfire* (RAVG) program creates vegetation burn severity products, like the burn severity index maps created in Portugal, that represent the wildfire effects to forested vegetation. These products are percent basal area loss, percent canopy loss, and composite burn index. Regression equations, based on field data (tree mortality data by species and size class), are used to derive the burn severity measures. These product helps other scientists, such as wildlife biologists, botanists, and silviculturists understand what to expect from the changed landscape for wildlife habitat, invasive weeds, and timber production. RAVG maps are typically created several months after the fire in order to capture post-fire delayed mortality. While an official RAVG product was not created for this assessment, a basal area mortality map with seven classes (known in the USFS as a *BA7 map*) was produced using similar methodology to the RAVG product. The BA7 map produced for the Serra da Estrela fire is calibrated using field data from the Northwest United States and, therefore, is not an accurate reflection of vegetation burn severity for this fire. It is only presented here for comparison of the post-fire remote sensing products used by BAER teams to conduct post-fire assessments. Vegetation burn severity (as measured by percent basal area mortality) can be higher than soil burn severity, as illustrated by comparing it to the BARC and soil burn severity (produced by USFS) (Figures 6, 7 and 8). Portuguese vegetation burn severity index is also shown here for comparison

Appendix C has descriptions of the remote sensing products used for USFS BAER assessments. While these products differ slightly from one another, field verification is an important step to help determine post-fire treatment applicability and priorities regardless of the map product used.

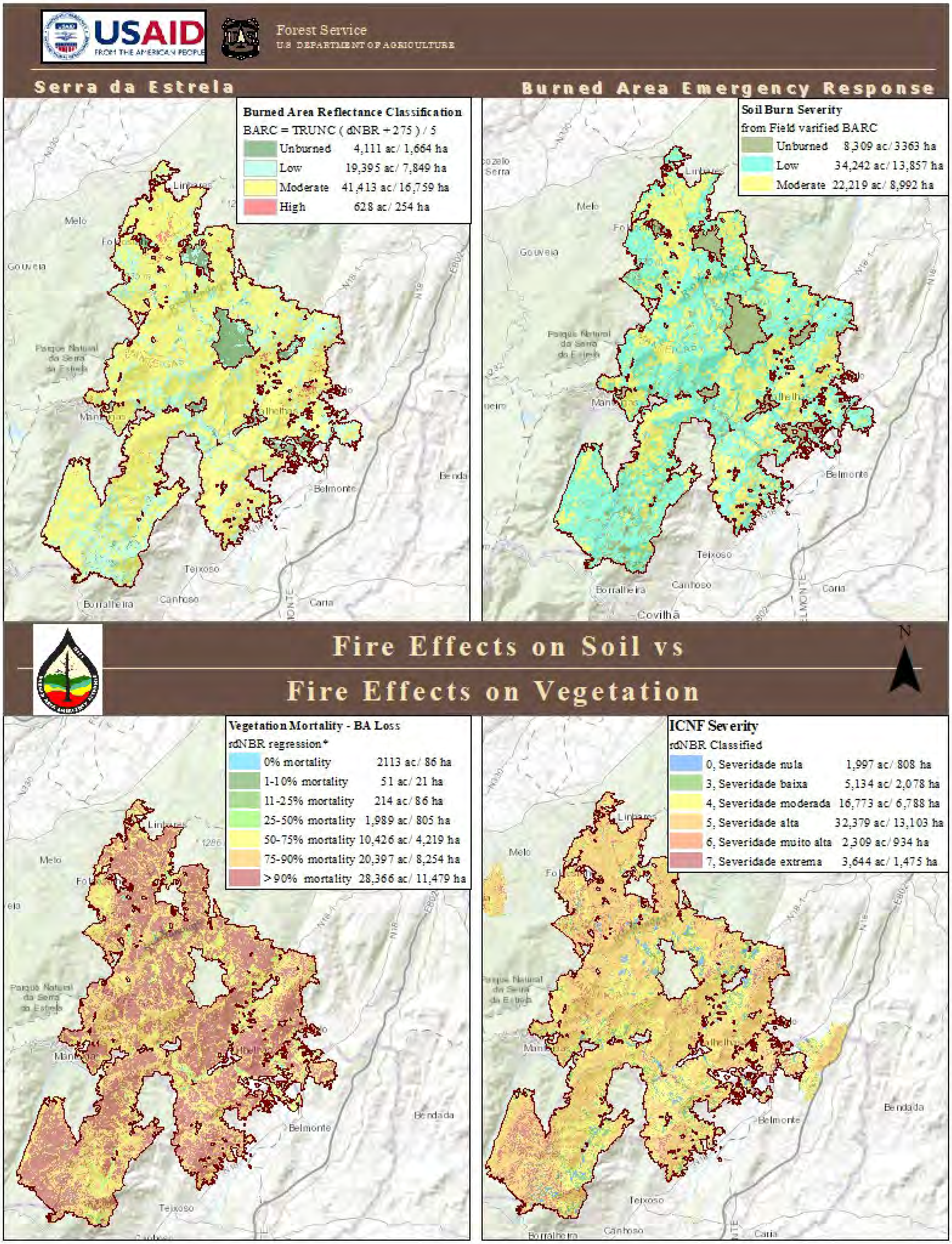


Figure 6. Comparison of satellite imagery products for the Serra da Estrela fire.

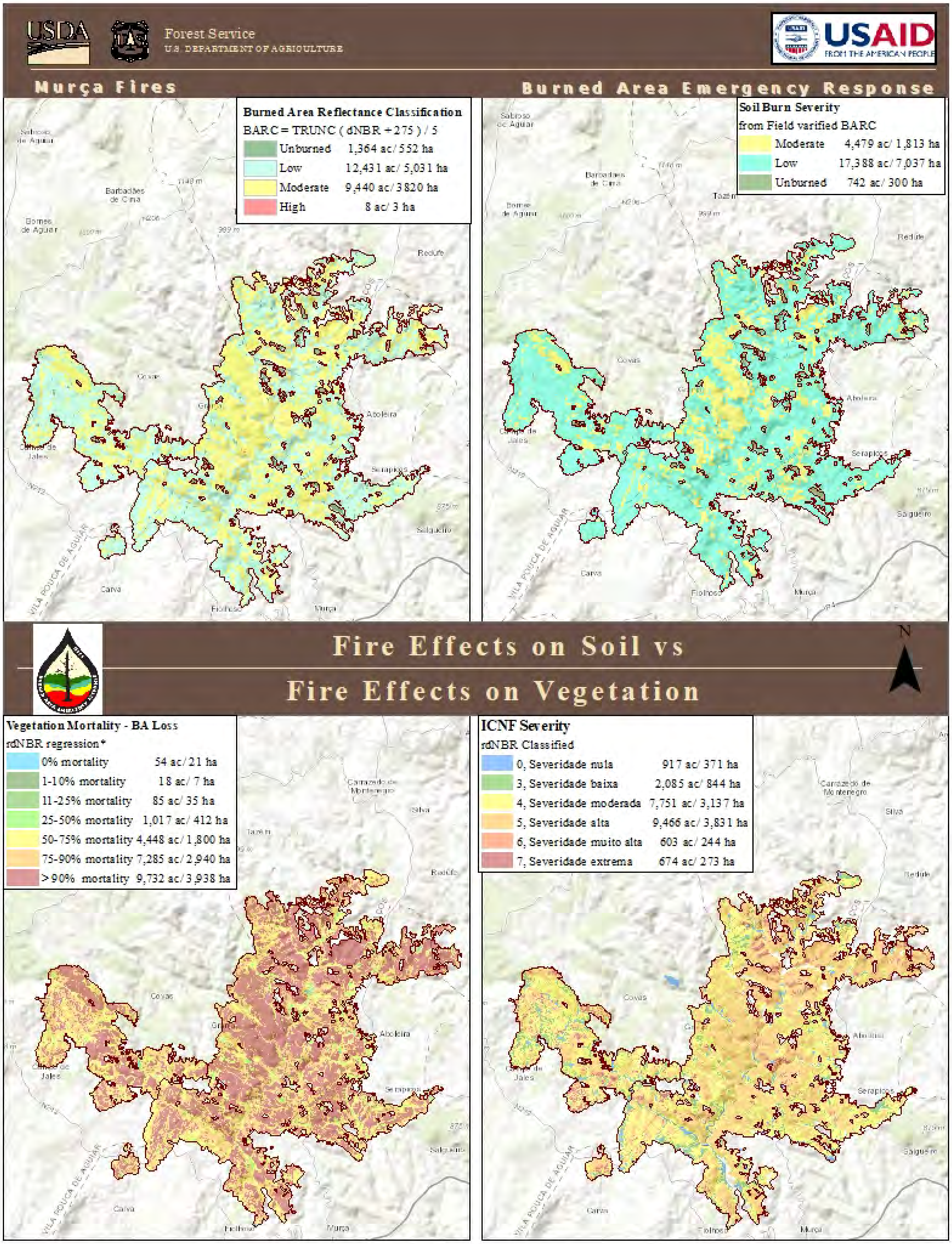


Figure 7. Comparison of satellite imagery products for the Murça fires.

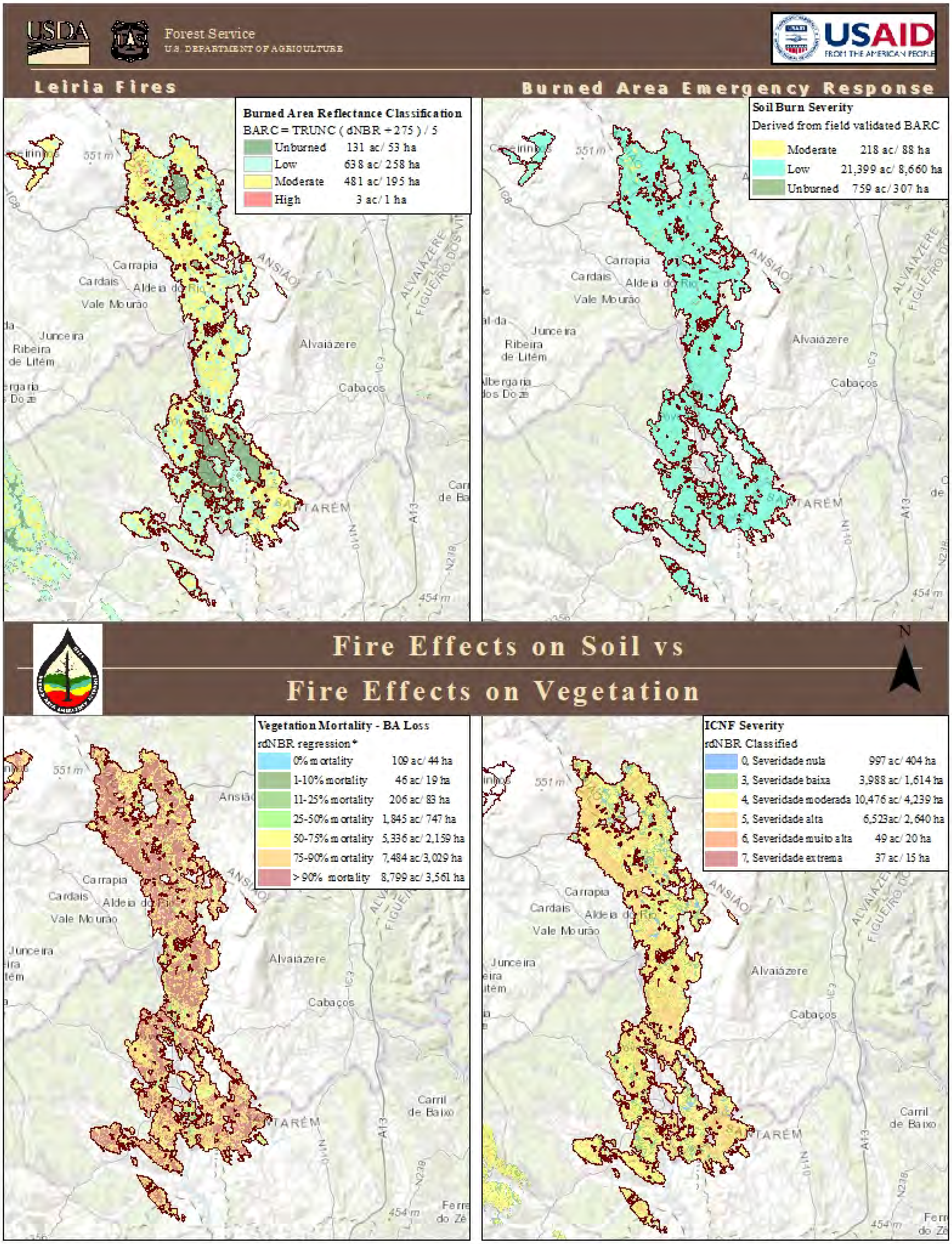


Figure 8. Comparison of satellite imagery products for the Leiria fires.

Anticipated Vegetation Recovery

Post-fire recovery varies greatly based on climate, vegetation types and burn severity. It is typical for recovery to take between 3-5 years for reestablishment of ground cover in the United States. The persistence of drought in the years following wildfires also delays the recovery time frame. Research in Portugal along with personal communications with Jacob Keizer indicate that vegetation recovery is closely tied to burn severity in the north and central regions of Portugal (Alegria 2022, Bastos et al. 2011, Van Eck et al. 2016). With the burned areas being mostly low and moderate soil burn severity, it is anticipated that the recovery in these systems will be rapid with ground cover approaching pre-fire levels within a year. Even with only a short period of time since fire containment, resprouting of trees and shrubs as well as emergence of forbs was noted throughout the burned areas (Photos 31-33).

Photos 31, 32, and 33. Vegetation recovery observed within the burned areas. (USFS photos)

Engineering and Roads

Critical values associated with the transportation system within the Serra da Estrela, Murça, and Leiria fires include life and the safety of ICNF employees as well as the public/private users of the road network. Post-fire threats to engineering infrastructure include increased overland flow, erosion, sedimentation, flooding, and debris flows that are likely to cause damage to roads and related infrastructure. Post-fire threats to the road infrastructure will persist for the next couple of years as the watershed recovers.

Current drainage features within these fires function exceptionally well in a pre-fire environment. These roads have self-sustaining drainage features that maintain road integrity. However, areas adjacent to and passing through areas of moderate soil burn severity were susceptible to increased sediment- and debris-laden flows causing the ditches to fill, infrastructure to plug and road sections to sustain damage. Complete post-fire loss of the road was not observed in any of the burned areas but was close in several locations; storms of higher intensity and duration could do further damage.

Workmanship of the current drainage structures is impeccable, very sturdy, and the main contributing factor to a sustained transportation network post-fire (Photo 34). Inlet catch basins built of hand-laid stone prevent scour and the outlet rock walls (where present) prevent back cuts and undermining of the road. Back cutting has occurred at various locations within the fires, typically where outlet sections or fillslopes lack armoring on the toe of the slope.

Existing drainage features, road locations, slope, soil type, soil burn severity, and anticipated watershed response all must be considered when assessing post-fire risk and proposing road stabilization treatments. Typically, only road segments below or transecting through areas of high and moderate soil burn severity warrant treatments. However, since soil burn severity does not always equal watershed response, it is always recommended to work with team members such as soil scientists and hydrologists to determine the risk and treatment recommendations suitable for each site. Key tools that aid in recommending treatments include the soil burn severity maps, Burned Area Reflectance Classification (BARC) maps, other satellite imagery, and debris/hydraulic flow models.

Photo 34. Team members admiring the hand work on existing drainage features. (USFS photo)

Suppression Impacts

Throughout the team's assessment of the wildfires in Serra da Estrela and Murça areas, it was evident that bulldozers were used to support suppression operations, creating many of the fire breaks. These dozer lines, created at the height of the firefighting operations two months prior, were still readily visible and noticeably eroding with recent rains. Some of these dozer lines were straight down very steep slopes (>45 degrees or 100% slope) and directly across both wet and dry stream/creek beds, creating a hazard for citizens and infrastructure that are located below the fire during periods of heavy rain.

Treatment discussion

Measures taken to reduce post-fire risk to critical values generally consist of point-protection measures, and larger-scale slope-stabilization measures. Even with large-scale hillslope treatments, it is difficult or impossible to eliminate the risk of elevated flooding below extensively burned areas. Consequently, point-protection measures are generally favored in USFS BAER and related post-fire work on private property. Measures to reduce risk to individual structures vary widely, though it is difficult to protect poorly sited buildings. However, villages in and below the burned area generally appeared to be built outside of flood-prone areas. Low-lying parts of Sameiro, in the Serra da Estrela fire area, are a notable exception.

In some areas, efforts to reduce erosion from burned hillslopes were underway at the time of assessment. This work included clearing obstructed road drainage features such as ditches and culverts, installing temporary road-surface drainage features, spreading wood chips adjacent to forested roads, constructing log check dams in some intermittent stream channels, and installing log and slash erosion features on hillslopes. Work to keep road drainage features functional is critical in the post-fire environment, and the prompt efforts undertaken thus far by ICNF and municipal partners have likely saved many kilometers of road from further damage during the October rains.

Hillslope treatments

Multiple hillslope treatments are being applied throughout the fire area – seeding, mulching/chipping, and log erosion barriers. Post-wildfire storm events in the moderate soil burn severity class on slopes greater than about 10° (~20%) are likely to result in accelerated erosion and sediment delivery. Hillslope treatments such as scattering of wood chips and construction of log erosion barriers may be effective at a site-specific scale and low rainfall intensities. However, these efforts are generally overwhelmed by heavier rains, and are generally not done at a large enough scale across larger watersheds to result in a measurable reduction of peak runoff or sediment loading.

In general, hillslope treatments to reduce effects from erosion and accelerated runoff should be limited to suitable slopes within high or moderate soil burn severity classes. For all hillslope treatments, the ideal slope range for maximum effectiveness is 15-30° (~30-60%). Treatments are generally not needed on areas of low soil burn severity across all slope gradients or in areas with moderate soil burn severity at slopes under about 15° (~30%), as extensive erosion and sediment movement are less likely in these settings. While burned slopes at gradients above approximately 30° (~60%) are likely to have extensive erosion, hillslope treatments such as seeding, mulching, or log erosion barriers are unlikely to effectively reduce this risk. Based on these categories of consideration, below are maps for hillslope treatment suitability on the Serra da Estrela and Murça fires. Using moderate soil burn severity and slopes between 16 to 31 degrees, only 3,080 hectares (7,610 acres), or 12% of the Serra da Estrela burned area, was found to be suitable for hillslope treatments (Figure 9). Similarly, for the Murça fires, 275 hectares (679 acres), or 3% of the burned area, was found to be suitable (Figure 10). There were no areas identified for the Leiria burned area suitable for hillslope treatments. These estimates are assumed to be the maximum hectares available for potential treatment as many areas with greater than 65% surface rock or with potential for needle cast would not likely need treatment.

Seeding

Post-fire seeding efforts have largely fallen from favor in the United States because of the lack of effectiveness in the year of the fire at preventing erosion. Robichaud and others (2000) reported that seeding had little measured effect in reducing first year post-fire erosion; seeding effects are more evident in the second and subsequent years. Treatment effectiveness is highly variable due to soil moisture at the time of germination and during initial seedling growth. Seeding shows the most effectiveness in the second year after the fire because of the mulching provided by the first year of grass growth. In addition, seeding is only recommended in areas where there is sufficient soil for seed-soil contact required for germination. Seed can also be easily lost due to wind and rain events so timing with pending weather events is recommended for optimum generation without loss of seed downslope. Given the robust vegetation recovery anticipated for these fires, if seeding is applied, the use of quick growing sterile grains should be considered if necessary for erosion control.

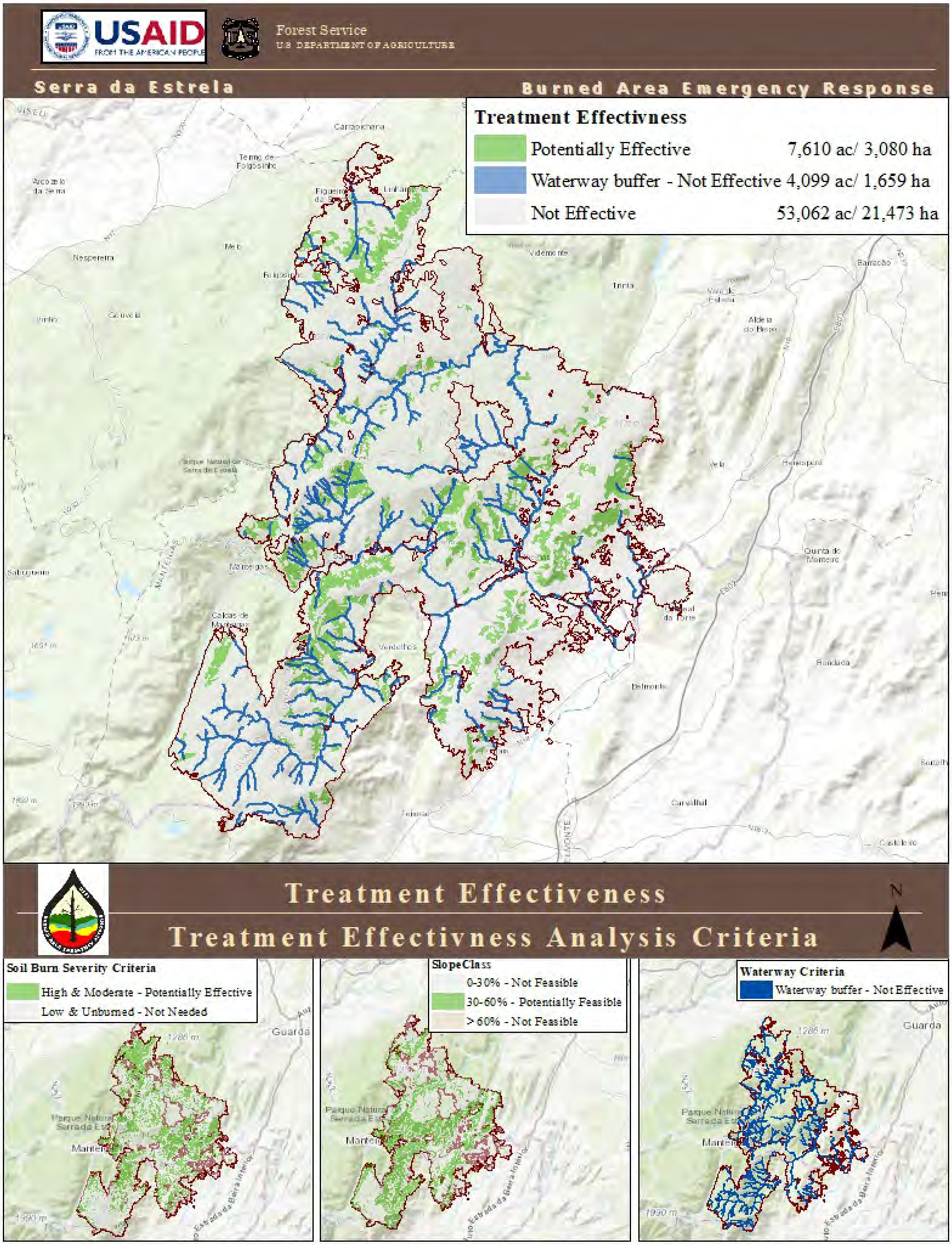


Figure 9. Hillslope treatment effectiveness map for the Serra da Estrela fire.

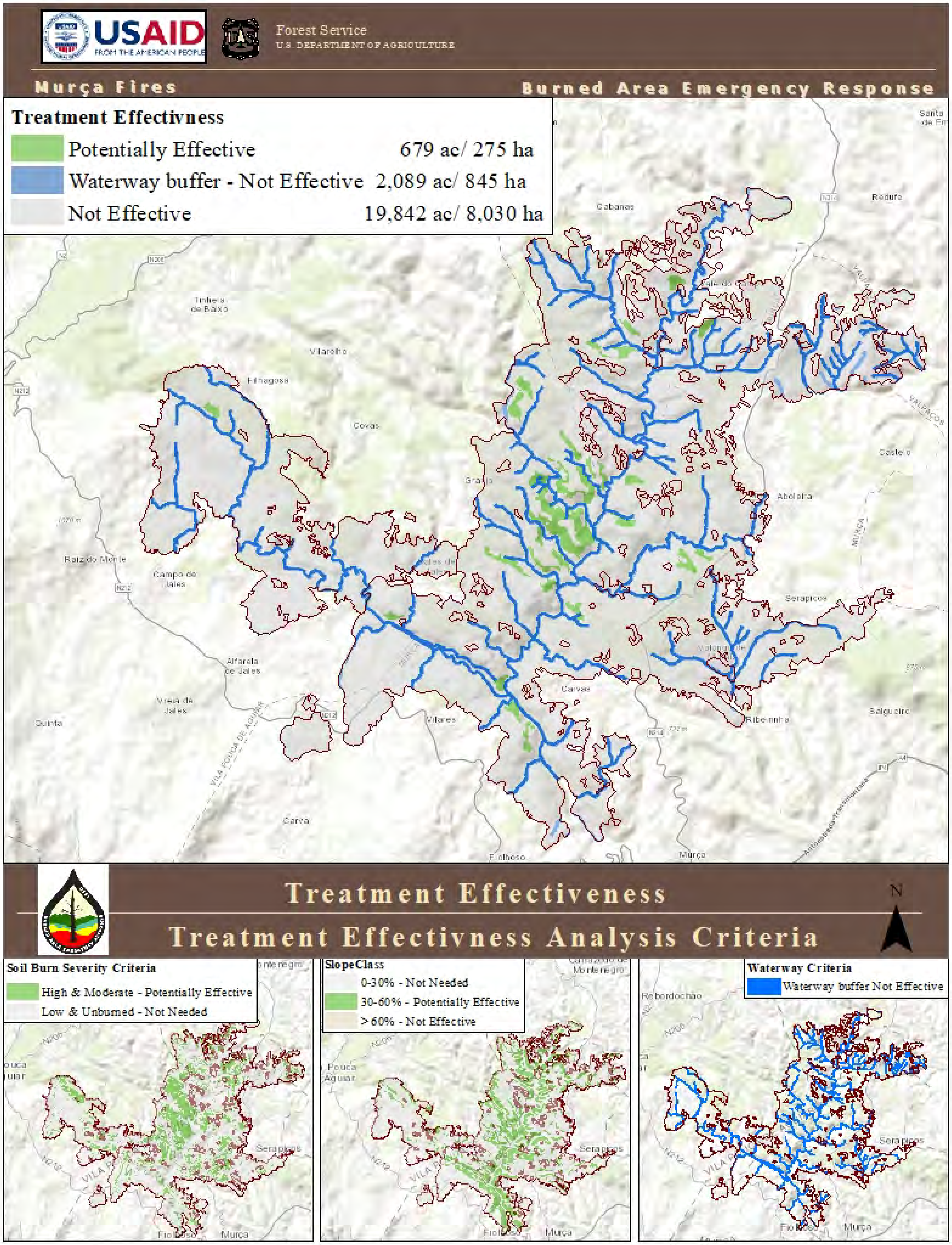


Figure 10. Hillslope treatment effectiveness map for the Murça fires.

Wood mulching

When evaluating wood mulching, the size and composition of the mulch is integral to the effectiveness. Wood products come in a variety of size compositions, measured in the predominant length of pieces as well as the percentage of fine material (pieces less than 2" in length). The chipping treatments along roadsides in the burned areas consists of smaller materials that will be less effective at erosion prevention as observed during the field review (Photo 35). Research has shown that small, rounded wood pieces are not effective at reducing erosion because they are easily displaced by overland flow (Foltz and Wagenbrenner 2010, Robichaud et al. 2013). Wood shreds composed of longer material are heavier and can interlock with each other, making the shreds less susceptible to movement by wind or overland flow. While the chipping treatments may not be as effective at erosion control as larger wood shred material, they do provide ground cover and organic matter to the soil to help with mitigate soil productivity loss. In addition, it is not recommended to mulch in areas with anticipated needle cast from species such as Pinus Pinaster that have large needles that can interlock and serve as an effective mulch cover.

Photo 35. Erosion and runoff occurring within a chipping treatment on the Serra da Estrela burned area. (USFS photo)

Log Erosion Barriers

Log erosion barrier effectiveness is dependent upon treatment density (number or length of barriers per hectare), precision of installation, as well as the frequency of sediment and debris removal and repair of barriers to extend their functional life. Effectiveness of barriers is also strongly dependent on rainstorm intensity. Log erosion barriers can be effective for smaller rainstorms but have been found to be ineffective during larger or more intense events (Robichaud et al. 2008, 2010). Improper installation and degradation over time also reduces the effectiveness of log erosion barriers (Figure 11). Furthermore, installation may cause enough soil disturbance to produce an increase in sediment yields, especially in the first few storms after installation. Land managers should carefully consider regional climatic, topographic, and ecological conditions when deciding whether to apply log erosion barriers as a post-fire erosion mitigation treatment. Barrier effectiveness is minimal on steeper slopes, and areas of low soil burn severity typically do not produce much sediment, rendering barriers unnecessary in these locations.

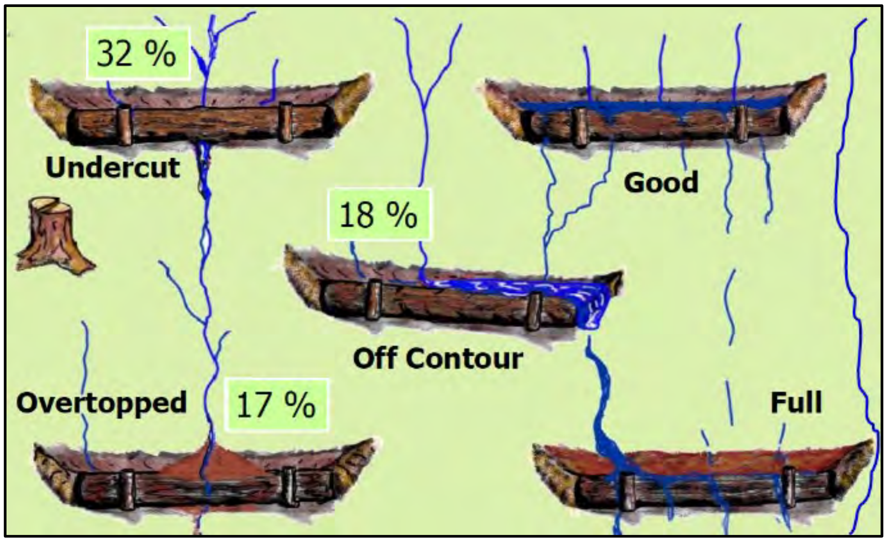


Figure 11. Log erosion barrier diagram showing common installation problems and failure points.

The technical team observed log erosion barriers and wooden check dams installed in various areas. Many of the log erosion barriers contained gaps between the logs and soil surface, which limits their effectiveness. During a rain event on 20 October, sediment-laden runoff was observed bypassing (flowing underneath) installed logs (Photo 36). Additionally, branches and slash were observed to have been placed on the upslope side of the log erosion barriers, reducing the potential volume of impounded sediment (Photo 37). If barriers do not function as intended or have filled, they pose an additional risk of continued or subsequent failures during future rains.

Photo 36. A log erosion barrier's failure point where log was not trenched into the soil in the Serra da Estrela burned area. A scoured path can be seen downslope of the failure point where concentrated runoff removed topsoil as it flowed downslope. (USFS photo)

Photo 37. A log erosion barrier with slash and branches placed on the upslope end of the barrier observed in the Serra da Estrela burned area. Sediment is captured but is limited in volume due to the additional material occupying the space. (USFS photo)

In-channel Treatments

In-channel structures such as log check dams can be constructed in headwater draws and small stream channels to reduce the probability of channel incision/erosion during peak-flow events, as well as to impound modest amounts of sediment in the channel (Photo 38). These structures are most effective in low-gradient systems (Robichaud et al., 2019). To meaningfully reduce channel erosion and sediment transport in the burned area, check dams generally need to be installed in great numbers throughout drainages burned at moderate or high soil burn severity. Effectiveness of log check-dams also depends on proper construction, including keying dams into banks to prevent side-cutting as well as armoring at the base of the downstream face of the dams to prevent undercutting.

Photo 38. Pre-fire rock check dams and post-fire log check dams installed on a small ephemeral channel. (USFS photo)

Sediment or settling basins are sometimes constructed within or adjacent to ephemeral channels to impound sediment-laden flood waters or debris torrents during a runoff event. The goal of the dams and basins is to reduce the amount of sediment carried downstream, thus reducing impact of high flow volume and sedimentation to the downstream critical value. These structures must have enough volume to store a high percentage of the fine sediment that would otherwise flow downstream. Settling basins are also more difficult to construct and more prone to fail in steep, dissected terrain such as occurs in much of the burned area. They require considerable effort and expense to install properly and have large disturbance footprints. Additionally, in order to remain effective, basins must be dredged of deposited materials after each basin-filling event, and the sediment removed from the site, which is an ongoing expense. While sediment basins can be cost-effective at a small scale or where extensive suitable terrain exists, they may not be a practical solution for reducing sediment transport in larger drainages across thousands of hectares of mountainous burned terrain.

Channel obstructions during a stream flood can lead to additional flooding from impounded waters, as well as failure of the structure, road, or other infrastructure at the point of obstruction. Clearing streams of large debris upstream of channel constrictions (e.g. culverts, bridges) can reduce the risk of an obstruction forming during a flood event. Any channel clearing should be weighed against potential impacts to aquatic habitat from removal of debris and should be done with a minimum of disturbance to stream banks and riparian areas.

Though there is sometimes a temptation to physically widen channels with heavy equipment, to increase the capacity of the channel to accommodate higher flood flows and debris, this practice should generally be avoided. Such work may reduce the flood level and associated impacts in the areas where the channel is cleared and widened. However, often these rivers then flow downstream into developed areas where channels are constrained by levees, walls, houses, and other structures. Flood peaks made higher by more efficient movement through the cleared and widened channel can cause greater damage in developed areas than if the upstream areas had been left with intact channels and riparian areas to slow the speed of flood flows and facilitate deposition of debris and sediment. Furthermore, standing trees in valley bottoms often trap debris in flood flows, attenuating flood peaks and reducing downstream impacts.

Road Treatments

The purpose of road “storm proofing” is to move water and debris more efficiently across a road to prevent or mitigate post-fire damage or significant road loss. Storm proofing treatments include maintaining and clearing debris from existing drainage structures such as rolling dips, culverts, culvert inlets, culvert outlets, ditches, catch basins, and grade reversals/grade sags. Prior to implementing road treatments ICNF should consult with any local Land and Resource Management Plans and/or other potential municipal authority for potential needed protections before performing work. This consultation may elevate a factor within the risk analysis. It is recommended, if necessary, to provide guiding authorities (laws, executive orders, regulations, and National/local guidelines) for any road-related work within the travel management system.

Most post-fire road related work uses standard road construction equipment such as dozers, road graders, backhoes, excavators, skid-steers, and compact loaders. Cleaning a plugged culvert often requires high pressure water assistance and hand tools for cleaning the inlets and outlets of culverts that cannot be cleaned with equipment. Manual labor is used for the placement of erosion control wattles, hazard/warning signs and medium to light gate installation. Materials needed are variable but include, geotextile fabric, riprap, erosion control wattles, culverts, and various culvert inlet protection devices such as inlet risers, snorkels, fencing, gates, signs, debris racks, debris deflectors and metal end sections.

Photo 39. Team evaluating road drainage in the headwaters above Vale de Amoreira (USFS photo)

Constructing additional drainage features on a road threatened by increased flows is an effective way to minimize erosion and damage to the road surface by reducing the concentration and velocity of water. A road designed for normal run-off usually cannot withstand increased water volume which enhances erosion potential and the possibility of complete road failure. Rolling dips (armored and un-armored), super dips, roadside ditches, lead-off ditches, water bars, catch basins and out-sloping of the road are the most common drainage features used for BAER treatments (detailed descriptions in Appendix E). Increasing the frequency of these features along areas of concern is an effective way to minimize road failures and sedimentation.

Sites that *likely* warrant treatment considerations include:

- Roads located below or transect through areas of high to moderate soil burn severity that are determined to have erosion risk due to increased runoff.
- Roads that intersect sustained steep slopes greater than 10 percent and are located on the lower two thirds of the slope within high to moderate soil burn severity.
- Road segments around or below areas of high soil burn severity that lead to areas of concern such as recreation sites, water collection sites and private property with permanent homes.
- Road segments/crossings with the potential to deliver sediment to streams through failure.
- Areas along roads that pose imminent post-fire threat to BAER critical values if the road fails.

Photo 40. Crocus blooming within the Murça burned area. (USFS photo)

Summary and Recommendations

The overall impression from the USAID-BHA/USFS BAER review for these fires is that while the soil burn severity caused by the fires in the reviewed burned areas was predominately low to moderate, post-fire risks remain for the communities and infrastructure within and below the burned areas. Many burned-area watersheds were already hydrologically responsive to rainfall prior to the fire and will be even more responsive due to post-fire conditions. However, the vegetation recovery is anticipated to be rapid with ground cover restored within 1-3 years, which will gradually attenuate the post-fire effects to watershed response (Photo 40).

Most of the recommendations provided below are already known to the ICNF staff and leadership. A tremendous amount of post-fire work has been completed by local authorities within the fire areas, including burned area assessments, hillslope and channel treatments, and recovery work on roadways. In addition to a discussion of standard USFS BAER methods, we have included a basic review of the analysis products provided by the ICNF staff as a part of the report and recommendations.

The recommendations provided are organized into similar themes. In addition to post-fire process recommendations, we have included general wildfire suppression and watershed management recommendations related to managing post-fire threats and response.

Post-fire Assessments and Funding

We recommend ICNF begin post-fire assessments as soon as it is safe to have staff enter the burned areas. USFS BAER assessments occur typically as the fire is nearing containment. Timing of assessments is planned so that satellite and model products can be validated through field observations and treatments designed and implemented prior to damaging storm events.

We recommend that all satellite products and models be validated by ground observations. Since there is a very strong disagreement between the vegetation and soil burn severities in the fires that we reviewed, we would advise that ICNF prioritize treatments by using soil burn severity and slope mapping of the fire areas. We further recommend prioritizing treatments by focusing on areas above or upstream from critical values where soil erosion, sediment transport, and flooding pose unacceptable risks and treatments can reduce those risks.

While we used soil burn severity and common BAER modeling techniques to evaluate treatment effectiveness, the post-fire soil erosion risk assessment completed for Portugal (Parente et al 2022) could also be incorporated into the review process. When comparing soil burn severity and erosion estimates derived from standard USFS BAER methods with the post-fire soil erosion risk assessment, the results highlighted the same areas of concern. While the products are based on different input data and spatial scales, both approaches can be used to refine the need for possible post-fire mitigation treatments.

While we realize much of this is outside of ICNF's control, identifying various funding sources for rapid, emergency response as well as longer-term restoration will help in implementing projects on the ground prior to damaging events. By using the prioritization tools as described above, ICNF can utilize limited resources on the areas of highest needs with the most chance of success. In addition, improving funding mechanisms between the national government and municipalities for post-fire response activities, such as road drainage improvement and hazardous tree removal, can increase visibility of action along with more rapid accomplishments.

Treatment Recommendations

Life and Safety Treatments

In USFS BAER assessments, there is a strong focus on treatments for the protection of life and safety. Much of this work is coordinated across several National and State agencies that all have a role in post-fire protections from land management agencies to weather and meteorological services and local emergency management. Recommended treatments for these fire areas include early detection and warning systems, post-fire hazard warning signs, and removal of hazard trees along roadways.

Early warning systems include a variety of methods to anticipate or observe flooding and debris flows and warn officials and potentially impacted populations of impending threats. The communities of Sameiro, Vale de Amoreira, Verdelhos, Valhelhas, Mascanho, Valongo de Milhais, and Quebrada de Cima, and other small villages and homes downstream of the Serra da Estrela, Murça and Leiria burned areas are at risk of increased watershed response to high intensity rainstorms and subsequent flooding. An early warning system that uses different warning stages combined with emergency response actions can provide local officials and the public with advanced warning of conditions that could result in dangerous flood flows, injury, or loss of life. A more detailed description of early warning systems can be found in Appendix D. For any early warnings, we recommend ICNF collaborate with weather forecasting officials (e.g. the Portuguese Institute for the Sea and Atmosphere—IPMA) to observe storm tracks (from Doppler radar, satellite imagery, etc.) and broadcast general warnings when heavy rains are moving toward the burned areas.

Post-fire hazard warning signs should be placed at entry points to the burned area and areas downstream of burned areas that are vulnerable to post-fire flooding. The signs alert the public to the changed conditions caused by the fire and the potential risks of traveling or recreating within the post-fire landscape. Similar signs should also be considered at streamside areas vulnerable to flooding where the public may choose to camp or recreate.

Fire-killed or damaged trees within striking range of roadways are a threat to public safety, both from direct impact and from loss of egress. Beyond the safety aspects of this treatment, it is generally less costly to remove hazardous roadside trees in a single effort than to cut out individual trees piecemeal as they fall over the next several years. These hazard trees can also be used for any chipping or mulching treatments identified for erosion mitigation needs.

Hillslope and Channel Treatments

If hillslope and channel treatments are used, implement these treatments where the conditions are most conducive for risk reduction.

- Optimal locations for hillslope treatments are between approximately 15-30° (~30-60%), and where soil burn severity was mapped as moderate with no potential for needle cast. Use soil burn severity in an erosion model to estimate the effectiveness of hillslope treatments in reducing erosion and peak flows at the relevant scales to identify the most appropriate locations for treatment installation.
- If log erosion barriers are used, work closely with the installation crews to ensure proper construction, and provide detailed descriptions and specifications. Know what value you are trying to protect and realistically evaluate the potential effectiveness of the treatment at the scale needed to achieve the desired reduction in risk.
- Carefully consider the potential effects of check dams in headwater channels. To achieve a meaningful reduction in sediment loading in a channel, dams must be built in great numbers—particularly in steep terrain. Properly installed and in sufficient numbers, check dams can prevent downcutting (channel incision) and reduce further erosion of gullies where not already cut to bedrock. There is little value in installing check dams in areas of low soil burn severity.
- In addition to the suitability screen described above (using soil burn severity mapping), avoid treatments in areas within basins that have a high probability of debris flows, based on evidence of past events. Hillslope treatments and check dams are not effective in preventing or mitigating debris flows.
- Political considerations often pressure land managers to implement mitigations regardless of whether they will be effective. Set appropriate official and public expectations of the outcome of hillslope treatments. Erosion control measures such as mulching or log erosion barriers can be effective in smaller rainstorms but are less effective or ineffective at higher storm intensities.

Road Treatments

Recommended treatments to protect engineering infrastructure include maintenance of existing drainage structures, construction of new road drainage and stabilization features, road infrastructure repair or removal, infrastructure point protection, hazard tree and rockfall mitigations, and hazard warning signs. This is recommended throughout the burned areas and especially in those watersheds above communities.

For the ICNF as it pertains to post-fire response, priority should be the efficient use of manual labor hours to perform the emergency response work. It is desirable to provide work and money on the front end to reduce the emergency response needed due to failing infrastructure. Assessing and determining key locations where treatments are needed early is key to effective and efficient response. This early detection will also be key to utilizing equipment while on site from suppression activities. When applying treatments to vulnerable roads, design to fail, not to sustain. Designing for failure will reduce overall sediment delivery while keeping transportation networks open for use. A detailed list of road treatments and engineering designs can be found in Appendix E.

Capacity and Collaboration

We highly encourage ICNF to continue and expand upon the ongoing collaborations with USAID-BHA, USFS, and University of Aveiro staff. We confirm the recommendation from the 2019 Schnackenberg report to work with local university staff and partners, as well as internal ministry staff, to establish a post-fire assessment and response process. This assessment and response process includes identifying a rapid post-fire assessment team of key resource specialists and developing post-fire guidance and training materials using existing protocols as well as local knowledge and experience. In addition, we encourage the further development of relationships with local municipalities in fire-prone areas to streamline cooperation and availability for post-fire response on municipal and private land.

We recognize and support the ongoing effort in ICNF to expand the capacity and ability of the staff to engage more in wildfire suppression activities. We encourage training and development of this new workforce in post-fire assessments, treatment recommendations, and implementation. We also recommend hiring staff from various backgrounds, including soils, hydrology and road engineering, if possible. Incorporating an interdisciplinary approach to post-fire response will improve creative thinking, problem solving, and innovation.

The team would also highly recommend and welcome further collaboration through professional exchange opportunities with ICNF staff. Of note, the USFS would welcome the opportunity to host ICNF staff to participate in post-fire assessments and response teams in the United States. To further build upon the collaboration from this review, we would recommend that staff who were highly engaged with our team in Portugal be involved in future professional exchanges, such as Hugo Rocha and João Loureiro, among others.

Monitoring

Monitoring burned area conditions and recovery, as well as treatment effectiveness, can assist in improving post-fire response. We recommend working closely with University of Aveiro staff in the development and implementation of monitoring mitigation efforts. We recommend further evaluation of implemented land and channel treatments over time, and especially after heavy rainstorms to assess function, refine methods and best practices, and determine whether repairs or clearing are needed to maintain or improve function in future storms. Monitoring should include tracking of rainfall amounts and storm intensities using precipitation gauges located in representative areas of the burned areas. In addition to rainfall amounts, measurements or estimates of peak stream discharge where significant floods occur can help in understanding what rainstorm magnitude triggers a flood response in various locations and will assist in forecasting hazards from future storms, and on future fires.

In addition to official data collection, the use of “citizen scientists” can provide additional information where there are data gaps. Consider facilitating a network such as the North America-based Community Collaborative Rain, Hail, and Snow Network (CoCoRaHS) where citizens can report and view data collected on precipitation and flood events.

Fire suppression actions

Suppression operations

1. <u>Fire “mop-up” best practices</u>: Several senior ICNF and AGIF officials have noted that more than half the area burned in the Serra da Estrela wildfire, including the most ecologically damaged areas, was a rekindled wildfire previously thought to have been suppressed. It was further noted that “rekindles”, the reignition of a wildfire from a heat source overlooked by firefighters during suppression, were common in Portugal. In addition to expanding the burned area, rekindled wildfires often threaten lives and homes, and create significantly more ecological damage than if the initial wildfire was suppressed as planned. Considering this continuing problem, the USAID team would also recommend standardizing and mandating appropriate “mop-up” as part of normal firefighting operations. Mop-up is defined here as the full extinguishment of all heat along the fireline, up to 50 meters into the burned side of the fire perimeter, using hand tools, chainsaws, and hands-on work in the soil and ash. Without following this international best-practice, fire officials in Portugal risk losing the public’s trust and risk personal liability if it is determined one did not suppress the fire fully nor ensure it was out before demobilizing resources. The following is a small sample of standard mop-up best practices in the United States, drawn from US National Wildfire Coordinating Group (NWCG) guidelines (NWCG S-130, undated).
    a. Mop-up is difficult, dirty, and lacks the excitement of initial attack and direct suppression; however, it is a critical phase in the suppression process because remaining burning debris may rekindle and threaten the integrity of the control line.
    b. The initial objective during mop-up is to secure the edge of the fire perimeter, then gradually work deeper into the fire until the required mop-up depth is attained on the entire section of fireline; this can be up to 50 meters into the fire from the edge.
        i. Start mop-up at the outer boundaries of the fire edge.
        ii. Slowly work toward the center checking for heat sources.
        iii. “Cold trail” to ensure all heat within 50 meters of the fireline is extinguished.
        iv. Look for visible signs of smoke throughout the day.
        v. Any hot spots must be thoroughly saturated with water to ensure the fire will not flare up.
    c. *Cold trailing* is a method of controlling a smoking or hot fire edge by carefully inspecting and feeling with an ungloved hand or by using thermal imaging to discover sources of heat, afterwards digging out every hot spot, and trenching any actively burning/smoking edge.
        i. Make sure the black edge is cold and out
        ii. When intermittent heat is found, isolate with small sections of fireline around the hotspot to connect cold black to cold black.
        iii. Special attention should be given where “firelines” were created only by water from firehoses, bulldozers or an airplane’s retardant/water; best

practices indicate that manually digging firelines is more effective in suppressing wildfires than use of water alone.

iv. Water and bulldozers can inadvertently knock hot embers into the "green" (unburned) side of the fireline, due to the impact from strong water pressure, aircraft speed, or lack of visibility in a bulldozer.

d. *Dry mopping* is the process of using cool mineral soil to mix in with hot ash/organic material to reduce its temperature below the point of ignition; this practice is often used in mop-up operations whenever a hotspot is found on or near the fireline. Dry mopping is a common practice in the US Forest Service where the availability of water is limited or logistically unfeasible.

e. Wet mopping, when available, is typically done with 20-liter water bags ("bladder bags"), whereby a firefighter sprays water using a handpump while another firefighter mixes the sprayed material with mineral soil, thereby creating a cool muddy paste, capable of extinguishing other heat sources nearby.

f. Firefighting handtools and chainsaws are important to have during mop-up, both to mix or dig soil and to cut brush and logs, in addition to scraping burning embers off of larger logs which cannot be moved due to their size or the steepness of slope. By scraping the embers or hot coals off of a tree or log, the heat source is removed, thereby extinguishing the fire; muddy paste plastered on the log (described above) can also assist with this practice.

g. Thermal imaging can be used to locate heat sources below the surface from either the ground or from the air. From either vantage point, the scan should be conducted overnight or early in the morning to avoid radiant heat from non-flammable objects warming in the sun (ie. rocks), which create false readings. Thermal imaging usage is recommended for all future wildfires in Portugal to assist with suppression and mop-up operations.

2. <u>Use of heavy equipment</u>: Bulldozers and other heavy equipment used in wildfire suppression can be effective tools but can also leave a lasting impact on the landscape. When using dozers in suppression, we recommend use of the following best management practices. The recommendations were drawn from the following sources from the US Forest Service and NWCG sources (USFS Dozer Boss, undated; NWCG S-236, 2013; Jaffe & O'Brien, 2009).

   a. The principles of direct, parallel, and indirect attack also apply to dozer line construction. Generally, all bulldozed material should be cast **<u>outside</u>** of the fireline and scattered (on the "green" side). In rare instances the dozer might be used on very small fires to push the burning edge into the fire area all the way around the perimeter. This is NOT a recommended practice.

   b. Install firelines where they can be properly drained.

   c. Avoid locating firelines across concave slopes or areas that will create troughs.

   d. If a fireline must traverse a stream, cross at a right angle to the stream or channel to minimize the disturbance.

e. Avoid wet areas such as seeps, springs, or meadows. Not only would disturbance result in resource damage but equipment can become stuck and fireline work can be delayed.

f. Scrape away only burnable vegetation and duff. Avoid deep cuts into the soil that will remove topsoil and reduce soil depth.

g. Don't push debris and sediment into streams.

h. Ensure water bars are constructed into dozer lines with solid soil; avoid loose soil and organic debris. (Figure 12 and Table 2)

    i. The water bars must be deep and firm enough to withstand abuse by 4-wheel traffic and breakdown by erosion or settling over time.

    ii. The outlets of water bars must be open to function properly. Place water bar outlets where the soil is well-protected by organic debris or natural rockiness so it can withstand runoff from the water bar at a 15° (30%) angle downslope.

    iii. Don't locate water bars where they will divert a natural water course. Soil and debris that is pushed to the side during fireline construction acts as a berm and can cause runoff to concentrate over long distances.

    iv. Break berms frequently between water bars to allow water to flow off the line onto undisturbed ground.

    v. During fireline repair, move soil and debris displaced by line construction back onto the repaired surface. This will help restore topsoil and soil cover.

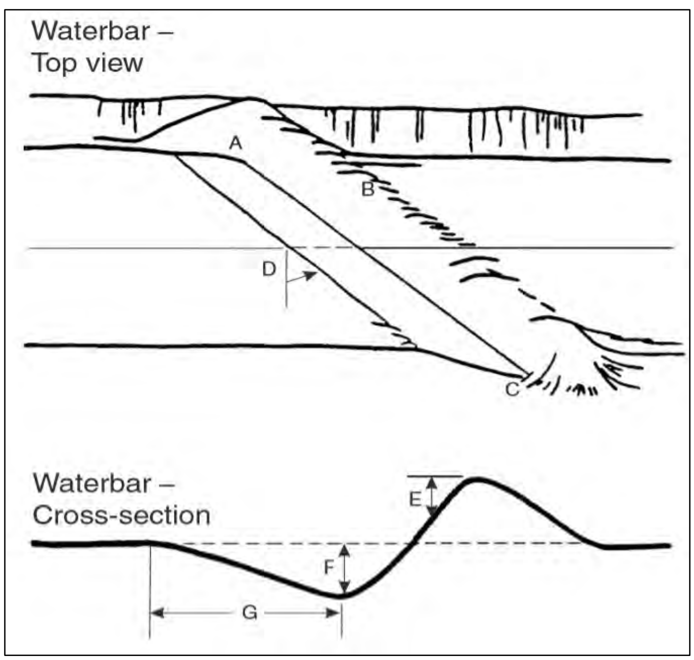


Figure 12. Diagram of proper water bar installation.

Table 2. Water bar spacing recommendations based on dozer line slope gradient.

Dozer line slope gradient – degrees (percent)	***Maximum water bar spacing (meters)***
3-5° (6-9%)	*120*
5-9° (10-15%)	*60*
9-14° (15-25%)	*30*
14°+ (25%+)	*15*

Suppression repair

Suppression repair includes efforts taken to repair or rehabilitate impacts to the landscape, roads, and other resources that occurred during fire suppression activities. We recommend the following:

1. Track suppression impacts while fire suppression activities are underway, ideally using a geospatial tool such as the ESRI AGOL Field Maps application. This effort will ensure that all suppression features and damage are accounted for, facilitating efficient repair after the fire. Consider assigning a specialist to focus on this task during suppression (the USFS has a firefighter position for this work—the *Resource Advisor-Fireline*).
2. Repair roads (especially drainage features) that were impacted by fire suppression traffic and equipment.
3. Rehabilitate suppression line created by dozers or other heavy equipment.
    a. Where not needed as a future road, fully rehabilitate the line using an excavator with bucket and thumb to de-compact the soil and interrupt drainage pathways downslope, leaving a lumpy, discontinuous surface. Drag woody material into the rehabilitated line and maximize ground contact by pressing material into ground with the excavator. Consider scattering seeds from native plants appropriate to the site.
    b. Where needed as a future road, install drainage features (e.g. water bars) to avoid erosion and gully formation. Avoid keeping steep dozer line on the landscape as these are difficult and expensive to maintain.
    c. Where dozer line crosses a stream, ensure that the line is properly rehabilitated or drained near the stream to avoid sediment delivery from the line. Repair banks as needed and scatter woody debris and mulch in the areas adjacent to the channel.

Salvage operations

Timber salvage of fire-killed trees is a common goal immediately following wildfires in forested land. Salvage work is usually planned quickly and implemented as soon as practical to maximize the value of the material removed. However, burned soils are particularly vulnerable to further degradation through vehicle and equipment traffic. The following general best management practices are typically followed in timber salvage work on lands managed by the USFS. Examples of timber operation best management practices are numerous (e.g. Montana DNRC, 2015; USFS, 2012).

1. Use sawyers (hand crews) where possible to minimize equipment impacts.
2. Develop a harvest plan: designate skid trails before harvest to minimize disturbance
    a. Use forwarders where possible to reduce impact of skidders dragging log
    b. Reuse existing templates and disturbances as much as practicable associated with harvest
    c. Avoid tractor travel on slopes greater than about 20° (~35%)
    d. Avoid travel on the fall line where possible
    e. Avoid skidding and other mechanical disturbance near valley bottoms
    f. Avoid off-road vehicle used when soils are wet
3. Residual material: Leave tops and limbs ("slash") on the hill
    a. Scatter slash in treatment areas to achieve an effective ground cover of roughly 85%. Fine slash (material less than three inches in diameter) is preferred. Avoid additional tractor use in scattering slash.
    b. Maximize ground contact of scattered slash to reduce erosion and accelerate decomposition
    c. Focus scattering of slash on skid trails and other disturbed ground
4. Rehabilitate log landings through decompaction and spreading slash.
5. Avoid using log landings near any type of likely flow or sediment transport conduit during storms, such as seasonal streams and swales, where practicable.
6. Roads:
    a. Minimize creation of new roads
    b. Ensure existing roads are properly drained (e.g. with drainage dips), especially at end of operations
    c. Rehabilitate road/stream crossings, which are likely to experience higher flows in the post-fire environment. Consider removing culverts where possible
    d. Consider decommissioning (removing from the landscape and returning to natural contours) any unneeded roads
6. Consider retaining some dead, standing trees for habitat purposes.
7. Aquatic management zones
    a. Consider excluding streams and areas of instability from harvest and new disturbance (i.e. landings, skid trails, roads) to protect water quality and riparian resources.

Pre-fire actions that facilitate post-fire response

Road construction and maintenance

Road construction and maintenance standards should be applied to ICNF road systems. This can help the agency pre-determine where to assess post-fire needs. The level of construction or maintenance standard is dependent on road type. Classifications should be given to roads to target higher use roads or where problem areas exist. Typically, US rural transportation systems have three main types of roads that are defined based on user comfort or what type of vehicles can access them (shown below). By taking the capabilities of a passenger car (two-wheel drive, low clearance) and the anticipated use, a categorization system can be applied to roads. In addition, proper road maintenance during pre-fire conditions, such as keeping ditches and culverts clean and maintaining road surface drainage, including crown, inslope, or outslope, and any drainage dips in properly functioning condition, can help reduce the workload needed in post-fire emergency situations.

- Maintenance Level 3 – High user comfort with design higher speeds, accommodates all vehicle types and typically surfaced with asphalt.
- Maintenance Level 2 – Moderate user comfort with moderate design speeds, accommodates most vehicle types and are usually categorized by aggregate surfacing.
- Maintenance Level 1 – Low user comfort with slow design speeds, accommodates four-wheel drive vehicles with high clearance and provide limited access and are constructed out of native material.

Terraced slopes

Proper drainage on terraced slopes (new and old): Research suggests that agricultural terraces can increase watershed response times as well as reduce peak flows and erosion for relatively common rainstorms due to their interruption of natural surface flowpaths and numerous breaks in gradient (Arnáez, et al., 2015). However, lack of maintenance and loss of groundcover frequently lead to failure of terrace walls and concentration of runoff and erosion (*Ibid.*). While many of the historic terraces observed in the burned area appeared to be in good repair, several points of failure were observed, including new wall collapse and gullying from rainstorms following this year's fires. Although it is difficult to predict the net effect of terraces in these burned areas, it is likely that unmaintained terraces will continue to degrade due to increased runoff, contributing to flood peaks and sediment loading in streams draining terraced watersheds.

Photos 41 and 42. Areas noted where terrace failures were contributing to post-fire runoff. (USFS photos)

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Photo 43. USAID-BHA/USFS BAER team.

Additional Acknowledgements

We would like to thank the following individuals in addition to the ICNF staff and Board:

Tiago Oliveira, Agency Integrated Management of Rural Fires (AGIF)

João Quadrado, Agency Integrated Management of Rural Fires (AGIF)

Jacob Keizer and Martinho Martins, University of Aveiro

Appendix A. Post-Fire Erosion Potential and Recommended Treatments Summary

Two different models were run to provide examples of typical modeling applications used in USFS BAER assessments. For the Serra da Estrela fire, both the Erosion Risk Management Tool (ERMiT) and Disturbed WEPPcloud-EU Post-Fire Erosion Predictor (WEPPcloud-EU) were used to model erosion potential. For the Murça fire, only ERMiT was used. No model runs for erosion potential were completed for the Leiria Fires because the overall burned area was estimated at 96% low soil burn severity, including the hillslopes above the village of Quebrada de Cima, which had the most potential to be affected. Furthermore, hillslopes in the Leiria fires contained gentle slopes and many areas were exhibiting natural recovery through the resprouting of woody shrubs and bracken fern.

Erosion Risk Management Tool (ERMiT)

The change in erosion potential and sediment delivery from pre- to post-fire conditions was estimated using Water Erosion Prediction Project (WEPP) resources standardly used in USFS BAER assessments. The most common tool used to predict post-fire erosion in the US is Erosion Risk Management Tool (ERMiT). ERMiT was used to model areas of concern in both the Serra da Estrela and Murça fires. ERMiT is used to predict the probability of a given amount of erosion potential based on single hillslopes and single storm runoff events (Robichaud and others 2006). ERMiT is a web-based application which provides a distribution of runoff-event erosion rates with the likelihood of exceeding these values. Inputs needed to run ERMiT are climate, vegetation type, soil burn severity, soils data such as soil texture and rock content, and hillslope length and gradient. Sediment delivery rates are estimated from one to five years following the fire, with and without the application of mitigation treatments such as seeding and mulch application. However, ERMiT model output accuracy is +/-50%, therefore the absolute numbers produced are best estimates. More model background and documentation may be found at http://forest.moscowfsl.wsu.edu/fswepp/.

ERMiT Model Assumptions and Inputs (example in Figure A1):

1. Custom slope lengths were created for ERMiT runs, generally 1000 feet were measured
2. Custom slope gradients were created for ERMiT and were measured generally on hillslopes with critical values below low and moderate soil burn severity
3. Soil surface textures mainly found throughout the burned area were sandy loams
4. Soil Rock Content averaged 50% to 100%, but ERMiT is limited to a maximum value of 50%

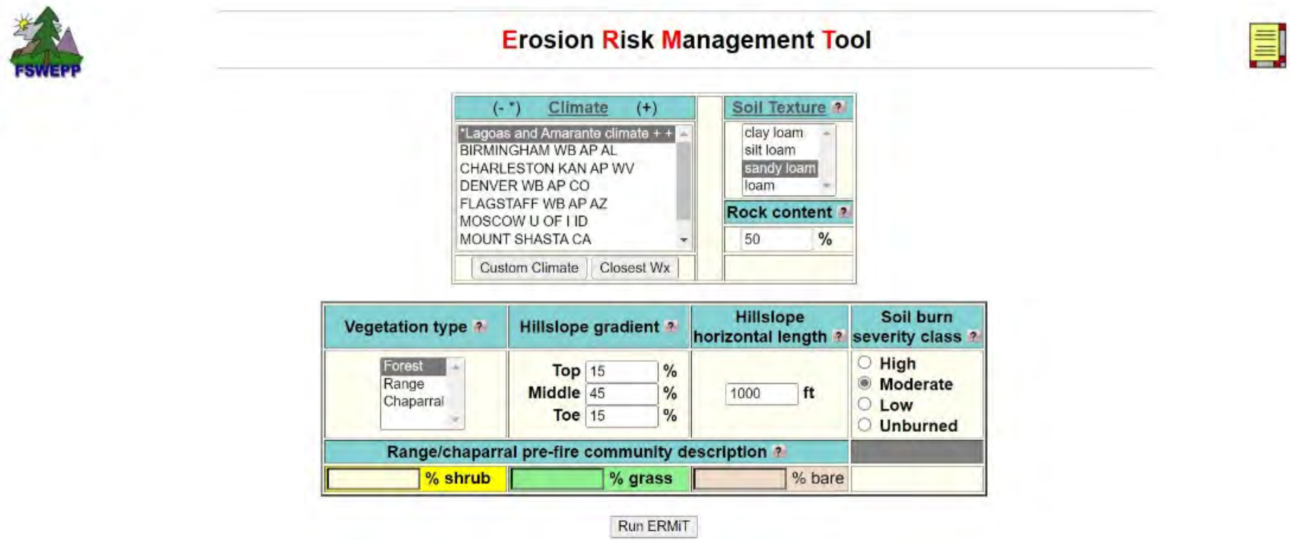

Figure A1. The ERMiT input screen with example run from a representative hillslope above the village of Sameiro.

The model-estimated pre-fire erosion rate from an average annual precipitation event for undisturbed areas was effectively zero across the fire area in ERMiT. Therefore, reported values represent fire-induced erosional increases for all drainages. Field notes observations from unburned areas included the presence of a continuous and thick litter layer under forested pine and shrub dominated areas and significant surface rock content, which preclude significant erosion from occurring on non-disturbed surfaces. However, as it was noted in the *Landscape History* section, soils have been heavily impacted by past management and land-use alterations and pre-fire erosion was observed, although amounts are not known. It should be noted that the modelling approaches used do not account for erosion or sediment delivery associated with roads, fire suppression lines, or other major disturbances. Where roads intercept and concentrate flows, slope erosion rates and delivery rates to streams may be higher than values reported here. These analyses also do not address road fill failures from plugged culverts or other infrastructure failures.

An important component of erosion models is the input for climate. The Serra da Estrela Fire and Murça Fires did not have a climate station within the burned area; therefore, a custom climate was generated for the fire area in ERMiT based on average monthly precipitation amounts provided to BAER specialists from Lagoa Comprida meteorological station. The Lagoa Comprida meteorological station has approximately 33 years of record, however there are data gaps throughout the years that are missing monthly averages for precipitation amounts. BAER hydrologists were further consulted to verify the modified climate was reasonable for the selected locations.

ERMiT modeling was run for several representative hillslopes within both fires to predict a potential range of erosion responses (Table A1). Modeling predicted erosion rates for a 50% probability runoff event within one year after the fire. Predicted rates in the Serra da Estrela Fire ranged from 32 MG/ha (14 tons/ac), up to 118 MG/ha (53 tons/ac) (example in Figure A2, Table A2). Representative hillslopes burned of the Valhelhas, Verdelhos, and Sameiro portions of the fire showing the highest erosion rates. Soils in moderate soil burn severity with long hillslopes and steep slopes yielded the highest predicted rates. Hillslopes representative of the Verdelhos portion of the drainage, with low soil burn severity and gentle slopes, had lower erosion rates of 32 MG/ha (14 tons/ac). Predicted rates in the Murça Fire ranged from 30 MG/ha (13 tons/ac), up to 91 MG/ha (41 tons/ac) (Table A3). Representative hillslopes above Curros within moderate soil burn severity and steeper slopes showed the highest erosion rates, while areas with low soil burn severity and gentle slopes above Valongo de Milhais showed the lowest rates.

Table A1. Hillslope variables used in ERMiT modeling

Hillslope Name	***Soil Texture***	***Veg. Type***	***Rock %***	***Top Slope (%)***	***Middle Slope (%)***	***Toe Slope (%)***	***Slope Length (ft)***	***Soil Burn Severity***
Sameiro – 1	Sandy Loam	Forest	50	15	45	15	1000	Moderate
Sameiro – 2	Sandy Loam	Forest	50	15	45	15	1000	Low
Vale de Amoreira – 1	Sandy Loam	Forest	50	30	60	30	850	Moderate
Vale de Amoreira – 2	Sandy Loam	Forest	50	60	50	45	950	Low
Valhelhas	Sandy Loam	Forest	50	30	60	30	1000	Moderate
Verdelhos – 1	Sandy Loam	Forest	50	30	60	30	1000	Moderate
Verdelhos - 2	Sandy Loam	Forest	50	0	15	5	1000	Low
Mascanho	Sandy Loam	Chaparral	50	30	60	30	900	Low
Penabeice	Sandy Loam	Chaparral	50	15	30	15	650	Low
Curros – 1	Sandy Loam	Chaparral	50	30	45	30	1000	Moderate
Curros - 2	Sandy Loam	Chaparral	50	30	45	30	1000	Low
Valongo de Milhais	Sandy Loam	Forest	50	0	15	30	750	Low

Sediment Delivery (ton / ac)

10-21-2022 -- sandy loam; 50% rock; 15%, 45%, 15% slope; 1000 ft; moderate soil burn severity [we

Sediment Delivery					
Probability that sediment yield will be exceeded	Event sediment delivery (ton ac^{-1})				
	Year following fire				
50 % go	1st year	2nd year	3rd year	4th year	5th year
Untreated	45.17	31.53	15.67	11.04	9.29
Seeding	45.17	20.1	11.04	9.29	9.29
Mulch (0.5 ton ac^{-1})	17.43	17.5	15.67	11.04	9.29
Mulch (1 ton ac^{-1})	17.32	17.34	15.67	11.04	9.29
Mulch (1.5 ton ac^{-1})	17.31	14.35	15.67	11.04	9.29
Mulch (2 ton ac^{-1})	17.31	13.99	15.67	11.04	9.29
Erosion Barriers: Diameter 0.25 ft Spacing 20 ft go ?					
Logs & Wattles	37.31	31.53	15.67	11.04	9.29

Return to input screen

Figure A2. The ERMiT results screen with example run from a representative hillslope above the village of Sameiro. ERMiT estimates provide post-fire erosion rates with and without treatments.

Post-fire erosion rates were compared with and without treatment because there is significant interest from ICNF in how effective land treatments may reduce erosion. We evaluated each of these treatments for the ability to mitigate the anticipated erosion from post-fire events at a hillslope scale. ERMiT estimates approximate sedimentation rates adjusted for theoretical treatments, including seeding, mulching and log erosion barriers. One limitation of ERMiT is a maximum surface rock content of 50% allowed, while the majority of the burned area had greater than 50% surface rock cover. Due to this, estimated erosion is likely higher than what will be observed in post-fire events.

Table A2. ERMiT Predicted Post Fire Erosion Rates, Hillslope Scale, Serra da Estrela Fire.

Hillslope Name	***Unburned Sediment Delivery (MG/ha)***	***Sediment Delivery (MG/ha) 2 yr event- Untreated 1st year***	***Sediment Delivery (MG/ha)- 2 yr event- seeding 2nd year***	***Sediment Delivery (MG/ha)- 2 yr event Mulch 0.5 tons/acre 1st year***	***Sediment Delivery (MG/ha)- 2 yr event Log Erosion Barriers Treated 1st year***
Sameiro – 1	0	101.3	45.1	39.1	83.6
Sameiro – 2	0.0	80.1	35.1	21.4	62.5
Vale de Amoreira – 1	0.1	105.3	49.0	44.0	105.3
Vale de Amoreira – 2	0.1	83.0	38.8	25.0	68.3
Valhelhas	0.1	118.2	56.0	48.9	105.4
Verdelhos – 1	0.1	118.2	56.0	48.9	105.4
Verdelhos – 2	0.0	31.9	13.4	10.5	0.0
Average Soil Loss	0.1	91.1	41.9	34.0	75.8

Table A3. ERMiT Predicted Post Fire Erosion Rates, Hillslope Scale, Murça Fire.

Hillslope Name	***Unburned Sediment Delivery (MG/ha)***	***Sediment Delivery (MG/ha) 2 yr event- Untreated 1st year***	***Sediment Delivery (MG/ha)- 2 yr event-seeding 2nd year***	***Sediment Delivery (MG/ha)- 2 yr event Mulch 0.5 tons/acre 1st year***
Mascanho	0.9	62.7	13.3	12.9
Penabeice	0.5	34.5	6.4	6.1
Curros – 1	0.9	90.9	15.6	16.7
Curros - 2	0.9	60.1	12.4	11.9
Valongo de Milhais	0.0	29.7	12.9	10.0
Average Soil Loss	0.6	55.6	12.1	11.5

In ERMiT, occurrence probabilities associated with the soil parameter sets are adjusted to reflect the increase in ground cover and subsequent small decrease in erosion after Year 2. The seeding rate is assumed to be approximately 9 kg/ha (8 lb/ac). Based on the ERMiT modeling results, there would be no appreciable change in first-year erosion rates and approximately 50% of the second-year erosion could be mitigated by seeding efforts if applied throughout the modeled watersheds. The average post-fire erosion rates in the second year for hillslopes treated with seeding ranged from 13 MG/ha (6 tons/ac) to 56 MG/ha (25 tons/ac). When averaged for the representative hillslopes, second year post-fire erosion rates are estimated at 42 MG/ha (19 tons/ac).

The average post-fire erosion rates for hillslopes treated with mulching at 1.12 MG/ha (0.5 tons/ac) the first year following fire ranged from 11 MG/ha (5 tons/ac) to 49 MG/ha (22 tons/ac). When averaged for the representative hillslopes modeled, post-fire erosion rates are estimated at 34 MG/ha (15 tons/ac).

Modeled results are based on installation of barriers at a 6 m (20 ft) spacing using 8 cm (0.25 ft) material. The average post-fire erosion rates for hillslopes treated with log erosion barriers treated the first year following fire ranged from zero to 105 MG/ha (47 tons/ac). When averaged for the representative hillslopes modeled, post-fire erosion rates are estimated at 76 MG/ha (34 tons/ac). Model results suggest that log erosion barriers, if installed correctly and in sufficient numbers, would reduce sedimentation somewhat on certain slopes burned at moderate soil burn severity.

While these numbers show a large decrease if treatments were applied, it does not take into account the suitability of the treatments based on soil burn severity and slopes. Further examination based on these conditions would be evaluated during a standard BAER assessment in the US.

Disturbed WEPPcloud-EU Post-Fire Erosion Predictor (WEPPcloud-EU)

WEPPcloud-EU allows users to describe numerous disturbed forest and rangeland erosion conditions at a hillslope scale, which is one of the major differences between ERMiT and WEPPcloud-EU. WEPPcloud-EU uses inputs from weather stations (in this case, the Portugal Amarante weather station) to generate simulated storm events from the known climate record and produces associated probability-based distributions of runoff events and erosion rates. Other model inputs include land use management, soils, and watershed topography (i.e., Digital Elevation Model (DEM) for a GIS tool, or slope length, steepness along the slope, and aspect for a single hillslope). Where data was unavailable, estimates based on field observations were used as default values.

WEPP Model Assumptions and Inputs:

1. Final soil burn severity was uploaded to determine the percent of disturbed forest per hillslope; baseline conditions were assessed by running the model without final soil burn severity and using the land use determinations in WEPP.
    - For example, in the Sameiro post-fire erosion at 52% shrub moderate soil burn severity and 49% grass/shrub low soil burn severity was used to run land use option.
2. Inputs are derived using the EU interface for soils
    - Soils for Sameiro were determined using the WEPP database and per hillslope. Loams, silt loams, and sandy loams were the most common. Single soil for watershed is also an option.
3. Portugal Amarante Climate Station was used for mean monthly precipitation amounts, maximum and minimum temperatures, and number of wet days. Although this station is over 100 kilometers distant from the burned area, and at considerably lower elevation, it was the closest station available in the WEPP database. Data from the Amarante climate station were used to develop 100 years of simulated climate in WEPPcloud-EU. Based on comparison to the Lagoa Met Station data, these mean monthly precipitation amounts are underestimated.

No results are being shared from this modeling effort. The model outputs did not appear to be appropriately aligned with anticipated results. While the ERMiT model produced similar results to the Portuguese post-fire soil erosion risk model, WEPP-EU did not produce realistic numbers and were highly underestimated for a post-fire landscape. It is known that the models are not very accurate and

50% variability as a good rule of thumb is used for model accuracy (Robichaud and Dobre, 2019). We would not currently recommend use of this model for erosion estimation in Portugal until more climate station information and better background model layers, such as soils information, are updated and incorporated.

Summary Discussion

Based on individual hillslope and soil characteristics as well as soil burn severity, we estimated post-fire erosion rates for human life and safety critical values below burned hillslope areas such as the villages of: Sameiro, Vale de Amoreira, Valhelhas, and others as shown in Tables A2 and A3. Predictions by the model suggest high sediment potential for all areas that were modeled, but background erosion rates should stabilize relatively quickly post-fire. Most soil erosion will likely occur from the first few post-fire precipitation events. However, soil burn severity is predominantly low and moderate throughout the fire perimeters. Areas are anticipated to have vegetation recovery within 1-5 years in low and moderate burn severity areas. Field observations revealed vegetation such as cork oaks, eucalyptus, bracken fern, scotch broom, and other shrubs were already re-sprouting in low and moderate soil burn severity areas. Additionally, low burn severities should have quicker vegetative recovery, and provide a needle-cast for mulch to cover exposed soils. Moderate soil burn severity areas may also have the potential for needle-cast accumulations. Soils also contain a high percentage of rock cover and fragments which will help reduce accelerated erosion. In addition, terracing was highly common throughout the burned areas which also aids to act as a sediment delivery interrupter in most cases. These ground conditions will lower erosion potential and sediment yield movement on the landscape, and we predict amounts were overestimated due to the data assumptions and overall accuracy of the models.

Natural recovery is generally the recommended treatment proposed by USFS BAER Soil Scientist Specialists because there is limited economically viable treatment options for erosion risk at a watershed scale. However, the proposed treatments by ICNF such as the current log erosion barriers, hillslope mulching, check dams as well as the treatments on roads will mitigate risks to soils in isolated areas. Furthermore, storm-proofing and storm patrol can help prevent concentration of flows onto adjacent soil areas and the resulting impacts to soil integrity and quality.

Further modeling data, results, and discussion are available upon request from the team’s soil scientists.

Appendix B. Serra da Estrela burned area runoff modeling example for Ribeira do Vale do Sameiro

This appendix outlines two different approaches to post-fire runoff estimation frequently used by USFS BAER assessment team hydrologists. As discussed in the main report, predicting stream flows in ungauged basins and estimating debris flow potential are challenging tasks, made all the more so in a post-fire setting. The two approaches reviewed in this appendix make use of the WEPP model (WEPPcloud-EU version) as well as a version of the runoff curve number (RCN) methodology originally developed by the US Soil Conservation Service (since changed to the Natural Resource Conservation Service, a partner agency to the USFS). The Wildcat5 version of the RCN method was used in this exercise. For both models, annual event probabilities of 50%, 20%, and 10% (two, five, and ten-year recurrence interval) were evaluated. The WEPPcloud-EU outputs are estimates of the peak flow for floods of various occurrence probabilities. Wildcat5 applies user-input rainstorms as inputs to estimate a peak flow value at the outlet of the modeled basin in response to the runoff generated by the specified rainfall event.

<u>WEPPcloud-EU</u>:
This tool is a relatively user-friendly, physical-process-based model that uses gridded digital elevation data, modifiable landcover and soil parameters from existing databases, user-entered soil burn severity data, and a stochastically generated climate based on existing climate records. It delineates a user-defined drainage basin into discrete analysis sub-drainages and can be used to evaluate runoff and erosion from drainages up to about 6.000 hectares (~15,000 acres). Climate, landcover, and soil data are somewhat limited outside of the United States, although some data are available for Portugal. WEPPcloud also has a single-storm input/output option, though it is still in beta form. The annual climate option was used for this exercise. The nearest climate station in WEPP's database was roughly 100 km to the south, and at a lower elevation, and thus significantly underestimates precipitation totals, which resulted in lower flow estimates than would have been predicted with better climate data.

<u>Wildcat5</u>:
The RCN approach assumes infiltration-excess overland flow and uniform drainage basin conditions. As such, it is of more limited value in undisturbed forest land, where infiltration-excess runoff is uncommon. As opposed to WEPPcloud-EU, this approach uses a single storm input to provide outlet runoff for that event and does not estimate erosion or sediment loading. The Wildcat5 version of the RCN method is in an Excel spreadsheet. User inputs include rainfall duration, rainfall amount, rainfall distribution over time, time of concentration as calculated using the basin mean slope and channel length, as well as runoff curve numbers to approximate the runoff coefficient (infiltration versus surface runoff). When used for post-fire flood modeling, the runoff curve numbers in the modeled basin are adjusted according to the soil burn severity within the basin.

Results from both models come in the form of flow values for various event probabilities, although WEPPcloud estimates runoff event probabilities from several years of climate inputs, whereas Wildcat5 provides a runoff flow rate for a given rainstorm probability, so they are not directly comparable. As noted above, WEPPcloud also provides estimates of watershed erosion and sediment delivery to stream channels, although this component assumes no occurrence of debris flows. WEPPcloud can also be used to provide input information to the Erosion Risk Management Tool (ERMiT), which can be used to assess the potential effectiveness of idealized land treatments at reducing erosion. The ERMiT model was run for this purpose on example hillslopes on the Serra da Estrela fires and is described above in the Soils appendix.

Neither model claims to produce results with a high degree of accuracy, and caution should be used in interpreting results (Tables B1 and B2). In addition to considerable potential model error, neither approach accounts for sediment or debris bulking of floodwaters, which can add considerably to the volume of flows, as well as increase probability of obstruction or damage to infrastructure. For these reasons, USFS BAER teams and others generally use results from post-fire runoff modeling to provide information on an approximate magnitude of change due to post-fire conditions, rather than absolute flow volumes for a given probability flood or rainstorm occurrence. These approximate magnitudes of change provide a rough sense of where critical values may be at greatest risk from post-fire flooding and help to guide potential treatment measures.

Table B1. WEPPcloud-EU Peak Discharge for Ribeira do Vale do Sameiro above Sameiro for three different event probabilities/recurrence intervals (RI).

Annual Exceedance Probability Flood Event	Pre-fire peak flow (m^3/s)	Post-fire peak flow (m^3/s)	Percent Increase
50% (2-year RI)	4.2	7.6	81%
20% (5-year RI)	13	22	69%
10% (10-year RI)	28	31	11%

Table B2. Wildcat5 Peak Discharge for Ribeira do Vale do Sameiro at the Village of Sameiro

Design Storm Event (mm)	Pre-fire peak flow (m^3/s)	Post-fire peak flow (m^3/s)	Percent increase
2-year, 60-minute (19.3)	0.5	9.7	1840%
5-year, 60-minute (27.7)	3.9	19.4	400%
10-year, 60-minute (33.3)	7.7	27.4	260%

A local understanding of baseflow and typical flood patterns of streams of interest is critical to help calibrate these models, particularly for pre-fire conditions. Although the team lacks familiarity with the streams and watershed response in the areas evaluated, and historical records are limited to larger rivers, some general conclusions can be drawn from this exercise. Although the two models produce different types of output data, the results are similar. The WEPP model can generally be expected to provide a more accurate estimate of runoff in pre-fire conditions in relatively undisturbed, forested watersheds than Wildcat5. However, in part due to the lack of representative climate data in WEPP, discharge estimates for both pre- and post-fire are likely to be underestimates. For this watershed, the

Wildcat5 post-fire results are likely more reliable for the storms likely to trigger a runoff response in the first few years following the fire. As stated above, the magnitude of increase is in line with expectations based on the field assessment and appears to be in approximate accordance with the experience in this watershed from the 12-13 September 2022 event. More accurate information on precipitation and flood peak from that event, if available, could be used to calibrate Wildcat5.

Generally, a USFS BAER team would estimate potential post-fire runoff from every watershed with sufficient burned area to pose a threat to important downstream values. Results would inform the team of general risk level, potential mitigating treatments, and relative risk among watersheds to assist in prioritization of treatments. The results of the analysis of Ribeira do Vale do Sameiro are likely not a surprise to anyone, particularly given the flood in September. However, watershed conditions remain similarly impaired, and this modeling effort suggests that another high-intensity, short-duration rainstorm could trigger another damaging flood. The results reinforce the need to ensure roads and drainage structures are prepared for the next storm, and that community leaders and emergency response officials prepare for the potential of further flooding in Sameiro.

Modeling data, results, and discussion are available upon request from the team's hydrologists.

Appendix C. Remote sensing products used in BAER

There are many satellite-derived products that can be used in post-fire assessments and many use similar terminology. BAER teams, when evaluating the need for post-fire stabilization treatments, are particularly interested in the post-fire soil properties that impact soil hydrological functions as these changes are associated with increased potential for flooding and erosion and primarily discuss soil burn severity. Fire or burn severity is also commonly used in a more general sense in the post-fire community. The term fire severity was born out of the need to provide a description of how fire intensity affected ecosystems, particularly following wildfires where direct information on fire intensity was absent and effects are often quite variable within and between different ecosystems. In this more general terminology, fire severity is the effect of a fire on ecosystem properties, usually defined by the degree of soil heating or mortality of vegetation. The severity of a fire depends on the fire intensity and the degree to which ecosystem properties are fire resistant. For example, a fire of the same fireline intensity might kill thin-barked trees but have little effect on thick-barked trees. Therefore, fire severity is, in part, a function of the ecosystem being burned and is not simply indexed from fireline intensity. If a fire has a long residence time, fire severity will usually increase. Forest ecologists define severity by the degree of overstory plant mortality. Tree mortality has been widely used as a measure of fire severity in conifer forests in North America that historically have been exposed to low-severity or mixed-severity fire regimes where normally there is substantial tree survival. Although the thresholds are subjective, in general, overstory mortality below approximately 30 percent is considered low severity, 30 to 70 percent is considered moderate severity, and greater than 70 percent is considered high severity.

More information on the different imagery products can be found at the Burn Severity Portal (https://burnseverity.cr.usgs.gov/).

Products from USFS' Geospatial Technology and Applications Center (GTAC)

Burned Area Reflectance Classification for Soil Burn Severity Mapping

All USFS Burned Area Reflectance Classification (BARC) datasets are provided to BAER teams through the USFS' Geospatial Technology and Applications Center (GTAC). A BARC is a satellite-derived data layer of post-fire vegetation condition created using the Differenced Normalized Burn Ratio (dNBR). The BARC has four classes, representing burn severity: high, moderate, low, and unburned. This product is used as an input to the soil burn severity map produced by BAER teams.

In addition to delivering the 4-class BARC data to field teams, GTAC also provides field users a continuous 256-class version of the BARC. This is called the BARC256. This dataset provides users the ability to adjust the break points between reflectance classes. Analysts at GTAC will color code the BARC256 image using the same classification scheme used for the BARC4 data, but the BARC256 will not be recoded into 4 classes. The color-coding on the BARC256 done by GTAC is meant to act as a starting point for field team members. Users can view the color scheme and adjust these break points as desired to make the final soil burn severity map using ESRI ArcMap applications.

BARC data products are not typically publicly available as they are preliminary datasets that are used to create the soil burn severity map. It is preferred to only share the final soil burn severity data publicly since it has been validated by the BAER team in the field.

BARC products include the following for each wildfire:

- Pre- and post-fire satellite imagery
- Burn area boundary shapefile
- Continuous BARC layer
- 4-class thresholded BARC layer
- Metadata
- Visualization products

The GTAC BAER Imagery Support Program hosts a web-based training every spring. The training consists of an overview of the program and the analysis methods it employs. It includes an instructor-led GIS demonstration of BARC adjustment to field observations. Sample data and instructions for three GIS exercises are provided. The training is generally 3-4 hours in length and includes both an overview presentation as well as hands-on exercises. A recording of the most recent training (2022) can be found at the following link:
https://edcintl.cr.usgs.gov/downloads/sciweb1/shared/MTBS_Fire/data/baer/using%20barc%20for%20baer%20support-20220413_100441-meeting%20recording.mp4

Rapid Assessment of Vegetation Condition After Wildfire (RAVG)

The RAVG program, managed by the USDA Forest Service Geospatial Technology and Applications Center (GTAC), provides a rapid initial assessment of post-fire vegetation condition following large wildfires on National Forests. Fires are typically mapped within 45 days after containment. RAVG products are generated using a two-date change detection process and regression equations that relate imagery-derived burn severity indices to field-based burn severity measures. RAVG analysis starts with a pair of moderate-resolution multi-spectral images (e.g., Landsat imagery), one from before the fire and one from after the fire. The image pair is used to derive a burn-severity index called the Relative Differenced Normalized Burn Ratio (RdNBR, Miller and Thode 2007), which is sensitive to vegetation mortality resulting from the wildfire event.

The RAVG program relies primarily on Landsat imagery (Landsat 8 Operational Land Imager (OLI), Landsat 7 Enhanced Thematic Mapper Plus (ETM+), and, in earlier years, Landsat 5 Thematic Mapper (TM)). As of 2019, imagery from the European Space Agency's Sentinel 2 satellites has also been used routinely. Other multi-spectral sensors can be used provided they have sufficient resolution and the necessary spectral bands. The preferred bands are the near infrared (NIR) and short-wave infrared (SWIR, around 2.2 micrometers), which are ideal for detecting the change from healthy green vegetation to dead vegetation, bare soil and ash. The two bands are used to calculate three indices: the Normalized Burn Ratio (NBR, one for each image), the Differenced NBR (dNBR, the change in NBR from the pre-fire image to the post-fire image) and the Relative dNBR (RdNBR, a modified dNBR that accounts for pre-fire vegetation density).

Regression equations are used to determine burn severity measures from RdNBR. The regression equations are based on field data (tree mortality data by species and size class) collected from many fires in the Sierra Nevada and northern California, and contemporary Landsat imagery. The burn severity measures are percent change (loss) in basal area (BA), percent change in canopy cover (CC), and a standardized burn severity metric called the Composite Burn Index (CBI). Thematic (classified) versions of each metric are then created from the continuous products.

Summary tables and maps are produced by integrating the burn metric raster data with existing vegetation and ownership data. The vegetation data are derived from the Landscape Fire and Resource Management Planning Tools Project (LANDFIRE) Existing Vegetation Type (EVT) layer, recoded into eight broad vegetation classes for RAVG purposes. An ownership layer is used to identify the following four classes: USFS (non-wilderness), USFS wilderness, non-USFS (non-wilderness) and non-USFS wilderness.

RAVG products include the following for each wildfire:

- Geospatial products, including imagery and derived data
    - Satellite imagery (Landsat or similar)
        - Pre-fire scene (spatial subset)
        - Post-fire scene (spatial subset)
    - Normalized burn ratio and related indices
        - Pre-fire normalized burn ratio (NBR)
        - Post-fire NBR
        - Differenced NBR (dNBR)
        - Relative dNBR (RdNBR)
    - Burn severity measures derived from pre- to post-fire change
        - Percent basal area loss (continuous and 4- and 7-class thematic versions)
        - Percent canopy cover loss (continuous and 5-class thematic versions)
        - Composite burn index (continuous and 4-class thematic versions)
- User-friendly visualizations
    - PDF map (burn severity measure and post-fire imagery)
    - Google Earth map (KMZ) with thematic data and imagery
- Summary table of affected area by vegetation class, ownership class, and burn severity classAncillary data
- Fire perimeter (shapefile)
- Masked areas, if any (shapefile)
- Metadata (text)

Additional details about each product follow. Formulas for derived raster data are included in the metadata for each fire.

- Burn severity measures. The primary geospatial products are raster datasets (TIFF format) representing burn severity measures.
    - Percent basal area (BA) loss represents the change in live basal area relative to the pre-fire condition. For the continuous version, values range from 0 to 100%. There are two thematic versions. The 7-class basal area loss raster (BA-7) includes the following classes:
        - Class 1: 0%
        - Class 2: 0% - < 10%
        - Class 3: 10% - < 25%
        - Class 4: 25% - < 50%
        - Class 5: 50% - < 75%
        - Class 6: 75% - < 90%
        - Class 7: 90% - 100%

- A 4-class version (BA-4) is created by recoding the classes:
  - Class 1: 0%
  - Class 2: 0% - < 25%
  - Class 3: 25% - < 75%
  - Class 4: 75% - 100%
- Note that a different recoding is used for the four classes in the PDF maps and tabular summaries:
  - Class 1: 0% - < 25%
  - Class 2: 25% - < 50%
  - Class 3: 50% - < 75%
  - Class 4: 75% - 100%
- Percent canopy cover (CC) loss represents the change in canopy cover relative to the pre-fire condition. For the continuous version, values range from 0 to 100%. The 5-class thematic version (CC-5) consists of the following classes:
  - Class 1: 0%
  - Class 2: 0% - < 25%
  - Class 3: 25% - < 50%
  - Class 4: 50% - < 75%
  - Class 5: 75% - 100%
- The Composite Burn Index (CBI) is a standardized fire severity rating based on a composite of effects to the understory vegetation (grass, shrub layers), midstory trees and overstory trees. Values range from 0 (unchanged) to 3 (highest severity). The thematic product included in the RAVG dataset has the following four classes:
  - Class 1 = unchanged (CBI: 0 - < 0.1)
  - Class 2 = low severity (CBI: 0.1 - < 1.25)
  - Class 3 = moderate severity (CBI: 1.25 - < 2.25)
  - Class 4 = high severity (CBI: 2.25 - 3.0)
- Note: In all of the burn condition raster datasets, areas that are masked due to clouds, cloud shadows, smoke, active fire, or other reasons, are indicated with either -9999 (for continuous data) or 9 (for thematic data).

- Other raster data include a subset of the multi-spectral imagery (e.g., pre- and post-fire Landsat imagery) used for the assessment, and the associated indices (pre-fire NBR, post-fire NBR, dNBR, and RdNBR).
- The burn boundary (perimeter) and masked areas, if any, are supplied in vector form (shapefiles).
- A map (PDF) of the burned area portrays the post-fire imagery and thematic burn severity.
- A Google Earth file (KMZ) allows for interactive exploration of the perimeter, thematic burn severity and imagery in the context of high-resolution imagery and other data available in the Google Earth application.
- A spatial summary table (Excel) lists affected area (acres) by vegetation class, ownership class and burn severity class.

RAVG products are intended primarily for use in assessing fire-related reforestation needs. RAVG data help staff on local units prioritize areas for further assessment and support reforestation funding requests and decisions. They facilitate post-fire vegetation management decision-making by reducing planning and implementation costs. RAVG data also serve a variety of related Agency objectives, such as wildlife habitat analysis and salvage harvest planning.

Note: The RAVG regression equations are not calibrated to non-forest vegetation. RAVG burn severity measures should be interpreted in light of existing (pre-fire) vegetation.

Monitoring Trends in Burn Severity (MTBS)

Monitoring Trends in Burn Severity (MTBS) is a US interagency program whose goal is to consistently map the burn severity and extent of large fires across all lands of the United States from 1984 to present. This includes all fires 1000 acres or greater in the western United States and 500 acres or greater in the eastern Unites States. The extent of coverage includes the continental U.S., Alaska, Hawaii and Puerto Rico.

The program is conducted by the U.S. Geological Survey Center for Earth Resources Observation and Science (EROS) and the USDA Forest Service GTAC. MTBS was first enacted in 2005, primarily to meet the information needs of the Wildland Fire Leadership Council (WFLC). The primary objective at that time was to provide data to the WFLC for monitoring the effectiveness of the ten-year National Fire Plan. The scope of the program has grown since inception and provides data to a wide range of users. These include national policy-makers such as WFLC and others who are focused on implementing and monitoring national fire management strategies; field management units such as national forests, parks and other national lands that benefit from the availability of GIS-ready maps and data; other national land cover mapping programs such as LANDFIRE which utilizes burn severity data in their own efforts; and academic and agency research entities interested in fire severity data over significant geographic and temporal extents.

MTBS data are freely available to the public and are generated by leveraging other national programs including the Landsat satellite program, jointly developed and managed by the USGS and NASA. Landsat data are analyzed through a standardized and consistent methodology, generating products at a 30 meter resolution dating back to 1984. One of the greatest strengths of the program is the consistency of the data products which would be impossible without the historic Landsat archive, the largest in the world.

MTBS data products have been utilized for a wide range of both research and operational support projects during the past two decades. They provide a unique historical record of high spatial and thematic resolution data consistently characterizing post-fire effects for documented and mappable large fires in the US from 1984 to the present.

In the MTBS project, "burn severity" refers specifically to fire effects on above-ground biomass. The definition is drawn from the National Wildfire Coordinating Group (NWCG) Glossary of Wildland Fire Terms and is based on the term Fire Severity, which is defined as: "Degree to which a site has been altered or disrupted by fire; loosely, a product of fire intensity and residence time."

The following additional statements further clarify the nature of the products developed by this project:

- Burn severity is a composite of first-order effects and second order effects that arise within one growing season.
- Burn severity relates principally to visible changes in living and non-living biomass, fire byproducts (scorch, char, ash), and soil exposure.

- Burn severity occurs on a gradient or ordinal scale.
- Burn severity is a mosaic of effects that occur within a fire perimeter.
- Longer term effects are controlled by variables that evolve after a fire and are beyond the scope of this program.
- Burn severity is mappable and remotely sensed data provide a measurement framework.

The following geospatial datasets and mapping products are produced for every MTBS fire. File format is noted in parentheses.

- Pre-fire Landsat 30m reflectance image subset (GeoTiff)
- Post-fire Landsat 30m reflectance image subset (GeoTiff)
- 30m dNBR image subset (GeoTiff)
- 30m RdNBR image subset (GeoTiff)
- 30m 6-class thematic burn severity (GeoTiff)
- Burned area perimeter (ESRI shapefile)
- Non-processing area mask (ESRI shapefile)
- FGDC metadata (text/XML)
- Page-sized burn post-fire Landsat image and burn severity map with burn severity statistical summary (PDF)
- Google Earth map with pre/post Landsat image, burn scar boundary and thematic burn severity data (KMZ)
- Statistical summary of burn severity by key GIS layers (dbf)
- Fire table containing key fire occurrence attributes (dbf)

Google Earth Engine (GEE) Normalized Burn Ratio (NBR) Vegetation Mortality Tool (BA7) – Product Produced by USFS Pacific Northwest Region

The following is an excerpt from "Google Earth Engine (GEE) Normalized Burn Ratio (NBR) Vegetation Mortality Tool", documentation of a tool created by Andrew Stratton (GeoTools GIS Analyst, Data Management Resources, U.S. Forest Service). Products created by this tool are derived using a similar methodology to that used by the Geospatial Technology and Applications Center (GTAC) to create remote sensing products for official use in BAER assessments.

In the past, post-fire assessment products have typically been created from a single pre-fire image and a single post-fire image. The GEE application takes advantage of the ability to work with image collections and derives pre-fire and post-fire imagery statistics based on satellite imagery collections that cover pre-fire and post-fire date ranges. Products are creating using the Sentinel-2 image collection. The method increases the likelihood that cloud and smoke-free will be available and reduces the influence of imagery noise. Pre-fire and post-fire date ranges should match to ensure that differences in vegetation are not a result of seasonal changes.

When reducing the image collections to a single image for analysis, pre-fire imagery is reduced to the 50th percentile (median). When creating NBR fire-severity products, for forest areas the most accurate results have been obtained when using an imagery collection captured one-year post-fire reduced to the 50th percentile (median). When using the application during an active fire season (the analysis is taking place for the current year), to capture the changes taking place the image collection is reduced to a lower percentile. Depending on the amount of imagery available, Sentinel-2 imagery (20m resolution) is reduced to a percentile in the range of 17.5 to 40. For new fires where not much imagery is available, it is recommended to reduce the post-fire image collection to the 17.5^{th} percentile. Fires that have been contained and put out and have imagery available over a longer period show better results using a post-fire image collection that is reduced to the 40^{th} percentile.

Note: for non-forested areas, due to green up that occurs the year following a fire, best results are usually obtained using a date range the year of the fire and reducing the statistic to the 40thpercentile for Sentinel 2 imagery. Sentinel-2 imagery generally provides better results for fire severity analysis than Landsat. Due to its temporal resolution of approximately 5 days, it is more likely that cloud free imagery will be available from Sentinel-2 than from the Landsat satellites, which have a temporal resolution of approximately 15 days. However, luck certainly plays a role in obtaining cloud and smoke-free imagery and there have been cases where Landsat-8 satellites were able to capture higher quality imagery than Sentinel-2 (i.e. Klondike 2018 fire).

Imagery Products:

- **NBR:** The Normalized Burn Ratio (NBR) is computed for each image using the NIR and SWIR bands.
    - S2 –NIR: B8A, SWIR: B12
    - NBR = (NIR - SWIR) / (NIR + SWIR)
- **dNBR:** The Differenced NBR (dNBR) is computed by subtracting the postfire NBR from the pre-fire NBR.
    - dNBR = (PreNBR -PostNBR)
- **rdNBR:**
    - rdNBR = (dNBR)/sqrt((abs(PreNBR)) + 0.0001)

BA (basal area) classes:

BA 4 class			
x (%)	**y (rdNBR value)**	**Grid Code**	**Description**
0	134.870	1	0% BA mortality
0.25	235.195	2	1 – 25% BA mortality
0.75	648.725	3	26 – 75% BA mortality
1	961.930	4	76 – 100% BA mortality
BA 7 class			
x (%)	**y (%)**	**Grid Code**	**Description**
0	134.870	1	0% BA mortality
0.1	166.485	2	1 – 10% BA mortality

0.25	235.195	3	11 – 25% BA mortality
0.5	406.480	4	26 – 50% BA mortality
0.75	648.725	5	51 – 75% BA mortality
0.9	828.133	6	76 – 90% BA mortality
1	961.930	7	91 – 100% BA mortality
Regression: $y = 134.87 + 259.38x + 567.68x^2$ where y = the rdNBR value and x = the % BA loss. (Reilly et al. 2017)			

Appendix D. Early Warning System Description

The communities of Sameiro, Vale de Amoreira, Verdelhos, Valhelhas, Mascanho, Valongo de Milhais, and Quebrada de Cima, and other small villages and homes downstream of the Serra da Estrela, Murça or Leiria burned areas are at risk of increased watershed response to high intensity rainstorms and subsequent flooding. An early warning system that uses different warning stages combined with emergency response actions can provide local officials and the public with advanced warning of conditions that could result in dangerous flood flows, injury, or loss of life.

The minimum level of response should consist of monitoring forecast models for potential precipitation events and Doppler radar and satellite-collected data for rainfall that is tracking toward a vulnerable burned area. When near-term (12 to 24 hour) forecasts suggest that atmospheric conditions may lead to the development of high intensity rainfall, flood watches should be issued for the potentially impacted burned area. In the United States, the National Weather Service will typically upload burn perimeters to their Doppler monitoring screens and will observe real-time storm development in the vicinity of a burned area. ICNF should coordinate with the Portuguese Institute for the Sea and Atmosphere (IPMA) similarly. Local meteorologists and hydrologists must determine appropriate rainfall intensity thresholds to trigger warnings. A common threshold used in the United States is a 15-minute rainfall intensity of 25 mm/hr. When a precipitation intensity threshold is met for an event heading toward a fire perimeter, a burned-area flash-flood warning is issued to alert of imminent flooding. These warnings generally provide 30 to 90 minutes of lead time before the event occurs, although such warnings do not always result in actual flooding when radar returns are used as the sole source of precipitation intensity observation.

Direct measures of precipitation and streamflow conditions can offer more certainty that a flash flood will occur, though they offer less lead time before a flood reaches communities of concern than radar-based warnings. In contrast to the use of existing Doppler radar for flood warnings, direct measurements require additional equipment and monitoring infrastructure. Two options for direct measurements include mid-watershed sensors and rain gauges if used with software and communication systems to trigger automatic warnings in vulnerable locations. With all options, local hydrologists and meteorologists should determine appropriate rainfall intensity thresholds to trigger warnings. Mid-watershed sensors on larger rivers with real-time reporting capabilities (via cellular or satellite connection) can provide warning of the imminent approach of flood waters with up to a 10–20-minute warning period. This option may be of limited value for the burned areas evaluated for this report, as burned watersheds above villages are generally smaller in area, limiting the effective lead time of a warning. Rain gages with automated real-time reporting capabilities (via cellular or satellite connection) can also be used if located in the headwaters of vulnerable watersheds and have the potential for up to an hour of lead time on warnings.

Prior to implementation of the warning system, responsibility for installation, monitoring, and maintenance must be assigned to a responsible agency and a method for sending alerts to people within the flood hazard area needs to be established. Telemetered gages will send notifications to the responsible entities about observed rainfall and stream flow. When thresholds are exceeded, a small number of local officials in the threatened areas are contacted directly by the on-duty meteorologist and warnings then need to be issued to the public.

The early warning system would require installation of telemetered precipitation and/or streamflow monitoring instrumentation that could provide near real-time data to emergency response officials. The ideal location for precipitation gauges is in the upper third of the watershed of concern in the headwaters. Instrumentation should be located near a road for ease of maintenance, and in an area where it will be hidden to minimize the potential for theft or vandalism. If streamflow monitoring equipment is installed, the location should be high enough in the watershed to provide response time if a flood is detected. As noted above, the smaller area of the burned watersheds above the villages of concern may make streamflow monitoring a less useful option here, due to shorter stream response time to rain inputs.

Table D1. Stages of Early Warning System

Stage	Notification	Trigger	Action
Stage 1	Flood Watch	Forecast models indicate a potential for high-intensity rainfall events	IPMA issues a flood watch with 12-24 hour forecast products and notifies key local officials of potential for flooding
Stage 2	Flood Warning	Conditions are conducive to a flood or debris flow occurring within the next 15 to 30 minutes (typically determined by observing storm tracks and intensities using Doppler radar). Rain gauges within the watershed of concern surpass a storm intensity/duration threshold.	IPMA issues burned-area flash flood warning
Stage 3	Evacuation Notice	Flash flood warning issued by IPMA.	Local authorities in the communities at immediate risk are alerted via phone call from on-duty forecaster; SMS message sent to persons within the flood risk area; flood warning siren activated by the local emergency manager

Municipalities vulnerable to post-fire flooding should consider developing an emergency flood response plan. This plan should include evacuation notification protocols in areas where cell service is not reliable (e.g. a flood warning siren), establishment of evacuation routes, identification of safety zones, and a procedure for identifying vacant buildings to reduce the need for time-consuming door-to-door notifications. Local officials would be encouraged to hold a public meeting to discuss the flood response plan components.

The watershed above Sameiro has been identified as a good candidate for installation of early warning system equipment. Although most other villages and communities located below burned watersheds were generally built out of flood-prone areas, early warning systems should also be considered for Vale de Amoreira, Verdelhos, Valhelhas, Mascanho, Valongo de Milhais, and Quebrada de Cima, and any other populated areas adjacent to streams draining the burned areas.

In addition to the protection of communities, motorist-alert signs on primary roadways in burned areas contribute to public awareness and safety. More expensive custom-message sign systems can be telemetered to receive specific warnings when storms are approaching or are underway, and runoff or debris over the roadway is anticipated.

Appendix E. Road Treatment Descriptions

Treatments shown below are for “storm proofing” and protection of a roadway. The purpose of storm proofing is to move water and debris more efficiently across a road to prevent or mitigate post-fire damage or significant road loss. Storm-proofing treatments include maintaining and clearing debris from existing drainage structures such as rolling dips, culverts, culvert inlets, culvert outlets, ditches, catch basins, and grade reversals/grade sags.

Most post-fire road work uses standard road construction equipment such as dozers, road graders, backhoes, excavators, skid-steers, and compact loaders. Cleaning a plugged culvert often requires work with high pressure water and hand tools for cleaning the inlets and outlets of culverts that cannot be cleaned with mechanized equipment. Manual labor is used for the placement of erosion-control wattles, hazard/warning signs and gate installation. Materials needed are variable but include geotextile fabric, riprap, erosion-control wattles, culverts, and various culvert inlet protection devices such as inlet risers, snorkels, fencing, gates, signs, debris racks, debris deflectors and metal end-sections.

Constructing additional drainage features on a road threatened by increased post-fire flows is another effective method to minimize erosion and damage to the road surface by reducing the concentration and velocity of water across the road.

Rolling Dips/Critical Dips

Rolling dips are constructed by excavating a drivable swale/depression on the road surface. These dips intercept and transport water across the road from the inside of the road or roadside ditch at strategically located points. If constructed properly, the water is dispersed to minimize road surface erosion from concentrated flows. The “lead-out” is the structure excavated to direct the flow of water off the road and onto the forest floor. The lead-out from rolling dips may be armored to further reduce the risk of erosion. The number of rolling dips needed depends on the slope of the road, predicted increase in run-off and the erosion susceptibility of the road material and surrounding soils.

Photos E1 and E2. Newly constructed Critical Dip, adjacent to existing culvert. (USFS photos)

Rolling dips can also be constructed upstream of existing ditch-relief culverts to act as a relief for surface water flow when the culvert becomes plugged—these are also known as critical dips. Rolling or critical dips can be used in place of culverts in many sections of road with low traffic volume.

Photo E3. Newly constructed Rolling Dip with Lead out Ditch (USFS photo)

Super Dips

The super dip is an effective and efficient feature to move water across the road surface. Super dips are typically used at larger stream-road crossings where culvert removal or culvert up-sizing are cost-prohibitive. To protect larger stream-crossing infrastructure under deep fills, the objective is to design the crossing to manage the failure of the structure to minimize damage to the road. This is accomplished by lowering the road profile and hardening surfaces that are likely to carry overflow. Armor the road and fill-slope with large angular rock to keep the road surface open and functioning. Apply a layer of road surface material on top of riprap for user comfort. In many cases the installation of a super dip negates future road repair and is a long-term solution to protect the road and allow the infrastructure to sustain elevated flood flows.

Super dips would have lessened road damage in many locations within the Serra da Estrela fire had they been in place prior to the September 2022 storms. In some cases, removing the top layer of asphalt would be required to lower the road profile. Removing material for 50 meters on either side of the constructed dip allows passage of traffic with high user comfort. Lowering the road profile allows water and sediment to cross the road and return to the channel on the other side of the road, rather than become diverted down the road or ditch line. Spending money to construct a super dip is typically less costly than replacing a damaged structure after a flood. These locations also need to be a priority for storm patrol to help prevent infrastructure failure for one to two years after a fire.

Photos E4 and E5. Armoring of Super Dip. (USFS photos)

Photos E6 and E7. Before and after construction of Super Dip – Notice lowering of the road surface. (USFS photos)

Cleaning of Roadside Ditches

Roadside ditches intercept slope run-off above a road and transfer it to a strategic point where the water is directed across the road via a culvert, rolling dip or similar drainage feature. Ditches can be armored by placing riprap check dams or wattles in the ditch to reduce the velocity of the water and minimize the risk of erosion. Roadside ditches are common on in-sloped or crowned roads. The depth and shape of the ditch is variable and depends on the predicted amount of flow expected.

Roadside ditches within all burned areas generally appeared to function well. Ditches generally had good depth and adequate volume to transport water and sediment to the crossings. Ditch construction varied across all fires but seemed to consist of “V” or “U” cross sections with approximately a 30-cm depth. Ditches were constructed out of concrete and native materials and showed minimal signs of plugging or failure. Keeping these ditches clean and free to transport water and sediment should be a high priority in the post-fire environment. Plugging of a roadside ditch can lead to multiple road failures and sediment additions to flood flows.

When cleaning a roadside ditch, rather than create roadside berms, it is important to remove the material (paved surface) and/or blade the material back onto the roadway (gravel or native surface). Roadside berms concentrate flow to a single failure point increasing potential failure and sedimentation. Removal of berms is recommended in post-fire roadway emergency response.

Photos E8 and E9. Roadside ditches in need of cleaning, Serra da Estrela and Leiria fires. (USFS photos)

Cleaning and Constructing of Lead-Out Ditches

Lead-out ditches drain water away from the road and are often associated with other drainage structures. Lead-out ditches relieve the flow of water from roadside ditches without the water crossing the road when they are constructed on curves but are most often associated with rolling dips.

Photos E10 and E11.A newly constructed (typical) lead-out ditch versus a lead-out ditch with maintenance needed within the Serra da Estrela fire. (USFS photos)

Water Bars

Like rolling dips, water bars are constructed by excavating a shallow channel into the road surface to intercept and direct water off the road from a ditch or the road surface, with a raised linear berm on the downslope side of the channel. Water bars differ from rolling dips in that they are usually not drivable and thus are used on closed sections of road. Water bars should be considered temporary and must be filled in once the potential for erosion is stabilized and the road is re-opened. The number of water bars needed depends on the slope of the road, expected run-off and the erodibility of the road and the surrounding area. They should **not** be used on roads that remain open to vehicle travel but can be modified if traffic flow is needed.

The depth of a water bar depends on the expected runoff, but 18” to 24” is common. They are typically as wide as they are deep. Again, modifications in depth and grade can be made to accommodate emergency traffic flow.

Catch Basins

Catch basins are constructed on the inlet (upstream) side of a culvert. They slow the velocity of the water captured in the ditch before it enters the culvert, reducing the potential for erosion. If the catch basin becomes filled with sediment and debris, it generally leads to a plugged inlet and failure of the crossing. Frequent maintenance of catch basins is strongly recommended for at least the first year after a fire. A critical dip (armored or not) on the down-gradient side of the crossing is also advised to help protect the road in the event of a crossing failure.

Hand-laid stone catch basins observed across all burned areas were exceptional in workmanship and function. The attention to detail in these structures is truly impressive and is a testament to the skill of the Portuguese road builder. In many cases these structures saved crossings and reduced road failures.

Protecting these structures for the first year after a fire is imperative to protecting the road and reducing sediment delivery into the system.


Photos E12 and E13. Typical catch basins seen across all fires. (USFS photos)

Outlet Protection

Back-cutting (erosion of the road fill-slope has occurred at various locations within and downstream of the burned areas, typically where outlet sections are not daylighted to an armored outlet or to the toe of the slope. Where possible, extending the outlet structure two additional sections (approximately 2 meters) and placing on a grade with the toe of the fill slope would prevent this back-cut. Protecting these structures should be a priority for emergency response, to avoid more costly repair work in the event of a failure. Where a rock wall was present on the outlet side, back-cuts were not observed.

Photo E14. Location on the Serra da Estrela fire where outlet protection is recommended. (USFS photo)

Road Out-sloping

Out-sloping a road is an effective way to disperse water, reduce concentrated flows, minimize erosion and reduce the probability of large road failures. To out-slope a road surface, cut the fill slope and deposit the material on the cut-slope/ditch side so the water can naturally drain from the road at all points, without concentrating. This reduces water velocity and spreads the water across the road surface, so it uniformly sheets across and off the road. For safety reasons, out-sloping should not be used on roads with a slope of more than about 6° (10%) or on an outside curve. Out-sloping is typically considered for closed or rarely used roads.

Out-sloping of a road is effective for the first year after a fire and is often considered a temporary measure. After one to two years, the road prism should generally be re-established to pre-fire conditions for safety and long-term maintenance considerations.

Photos E15 and E16. Typical out-sloping (fill slope pull back). (USFS Photos)

Storm Inspection and Response ("Storm Patrol")

Storm inspection and response keeps existing culverts and drainage structures functional. A crew identifies problem areas and cleans sediment and debris out of culvert inlets and other drainage structures during and after storm events. A designated crew of inspectors and equipment operators with equipment must be available to minimize response time. Monitoring weather forecasts is critical for early response to road damaging storms. Timing is important to ensure the safety of personnel and equipment during the response effort.

Crews with ICNF are currently performing storm inspection and response and should continue to do so. Concentrating efforts on areas of concern on the highest priority roads will help protect needed crossings where labor and equipment are scarce. Storm inspection is only good if a response is ready to follow and keep water flowing and infrastructure functioning properly.

Photo E17 – Storm inspection and Response, keeping infrastructure flowing. (ICNF photo)

Riser Pipes

Riser pipes are typically installed on road-stream crossings with large (deep) fills, when replacing or removing the culvert is not economical. There are no standard designs due to the uniqueness of each situation. Working with hydrologists can provide flow rates and recommendations for each specific location to ensure the design will be effective.

Riser pipes are installed on culvert inlets to increase the capacity of culverts and protect the culvert from becoming plugged with debris. Riser pipes are best constructed out of corrugated metal, sized for each location, and installed vertically at the inlet of the culvert. Risers can be modified to custom-fit each location. Risers have perforations, usually above the normal flow line of the culvert, that strain out debris and allow water to pass into the culvert in the event of an inlet obstruction. The top of the riser should have a grate to prevent debris from entering and plugging the riser and culvert. Riser pipes are considered temporary for 1-2 years with a primary purpose of preventing culvert plugging while post-fire runoff response is elevated. These structures can save considerable effort in unplugging culverts during and after storms.

Photo E18. Riser pipes at a stream crossing. (from afterwildfirenm.org)

Relief Culverts

Relief culverts are sometimes installed at road-stream crossings with large (deep) fill, where the cost of removing or modifying the existing culvert outweighs the need or cost of repairing road damage if nothing is done. Relief culverts add additional hydraulic capacity and only function when the existing culvert reaches its hydraulic capacity or is plugged. The size of the relief culvert depends on the size of the existing culvert and the expected increase in flows, as well as site limitations. The relief culvert is typically installed above the flow line of the existing culvert so that it only functions when the existing culvert is full or plugged.

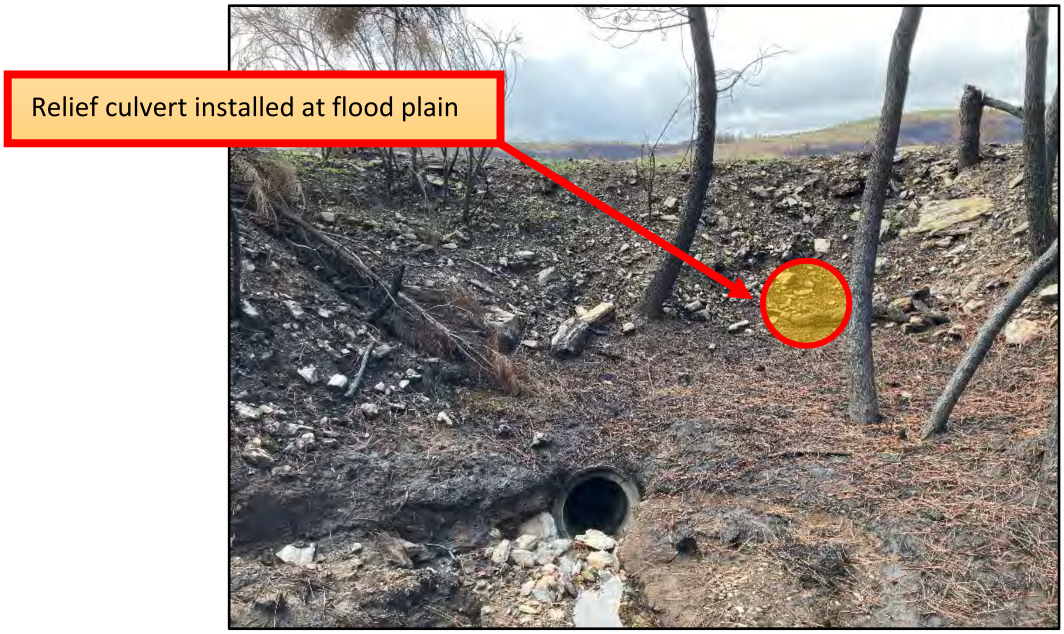

Photo E19. Relief culvert example, Serra da Estrela fire (USFS photo)

Debris Racks and Deflectors

Debris racks placed across a stream channel protect culverts from plugging. Debris racks catch debris and sediment before it is transported into a culvert. Debris rack designs are based on the type and size of the debris expected to threaten the drainage structures, and the channel width. Debris racks are constructed of heavy rail, steel, wood, or chain-link fence material. Debris racks require regular maintenance and cleaning to remain effective.

Debris deflectors divert/deflect water and sediment flow away from the main channel leading to a culvert or other drainage structure. Deflecting the flow from side channels minimizes the volume of water and sediment delivery into the main channel and reduces the chance of plugging.


Photos E20 and E21. Steel debris rack at culvert inlet (left), log debris rack higher in drainage (right). (USFS photos)

Ditch/Channel Clearing

Clearing wood and slash out of ditches and channels is necessary when the transport of slash could cause blockage to downstream structures. The escaped water can cause severe damage to roads and cause excessive erosion when the water begins creating a new channel and flows around culverts and other drainage structures. Clearing debris from channels for 100 to 200 meters upstream of the structure is generally advised.

Photo E22. Recently cleaned ditch line in the Serra da Estrela fire. (USFS photo)

Road Hazard Signs

Road Hazard Signs alert drivers and recreational users to potentially hazardous conditions created by the wildfire and alert drivers to closed roads due to post-fire hazards. The USFS Manual on Uniform Traffic Control Devices (MUTCD) and Forest Service Manual (FSM) 7731.5 specify the sign type, size, shape, and color of signage on National Forest lands in the United States. All signs installed on National Forest System Roads (NFSRs) in the United States must follow the MUTCD and FSM 7731.15 specifications. A person trained in sign management should review the selection and location(s) of the message. Signage is an effective way to alert the public of hazards that are present in a post-fire environment. In some cases, signs can reduce the liability of local governments if injuries or damages occur within the fire perimeter once closures are lifted.

*Photo E23. Typical installa*tion of roadside hazard signs for post-fire conditions. *(USFS photo)*

Temporary Road Closure

Road closure devices are necessary when there are hazards to the public such as potential debris flows or flooding, or unstable trees and rocks on or adjacent to the road. If the road does not need to remain open and the cost of making it safe for the public is prohibitive, then the road should be closed. Road closures can also be used to protect sensitive areas or areas that are designated to be left to naturally recover. Preventing road damage due to unstable roadbeds is also a viable reason to close a road. Gates, concrete barriers, and natural materials such as boulders are the most common types of road closure devices. Fencing and falling trees across the road are also used for closing roads.

Photo E24. Typical temporary road closure gate. (USFS photo)

Hazard Tree Mitigation

Hazard trees should be removed along roadsides where travel is to remain open, and removal of identified trees is allowed. Concentrate on sections of road that traverse moderate/high soil burn severity and around any areas of concentrated maintenance work (e.g. at drainage crossings).

Photos 25 and 26. Typical hazard tree issues (left), hazard tree removal needed (right) Serra da Estrela. (USFS photos)

Rockfall Mitigation

Mitigating risk from rockfall is an important consideration for the life and safety of both ICNF employees and the public, as well as for the protection of infrastructure. The most effective treatments for life and safety are area closures and warning signs. There are times when closures and warnings signs do not meet the risk management objective for life and safety and physical treatments of rock-fall must be considered. If rockfall mitigation measures for life and safety are needed, the treatments are generally limited to areas at which people are invited to congregate (i.e., parking lots, trail heads, scenic overlooks) and not the general ingress and egress routes of traveled ways.

Most rockfall treatments are completed for protection of infrastructure in both recreation and cultural resource sites. Rockfall has the potential to damage infrastructure within the fall zone of these threats. Assessments to identify these threats in areas of potentially major or moderate consequences should be completed during the post-fire assessment. This assessment should be the minimum needed to identify unacceptable risk areas so the appropriate response can be implemented immediately.

The removal of vegetation and soil by a wildfire typically leads to an increased incidence of rockfall. Dry ravel – the movement of individual particles downslope in the absence of water – is a gravity-driven process in which unconsolidated soils and rock move downslope. This process is prevalent in some post-fire areas where stabilizing surface vegetation and organic litter is lost. Rockfall is one type of dry ravel in which rocks dislodge from slopes and roll, slide or bounce downslope until their energy is dissipated on lower-angle slopes or they impact objects of larger mass. Rockfall is most likely to occur during and immediately following wildfire, then declines in likelihood and may dissipate almost completely after one year, although it is exacerbated by rain and treefall. Critical values in the path of rockfall could include vehicle or pedestrian traffic on system roads and trails, facilities, administrative sites, cultural sites, and natural resources. Slope geometry and material composition are the key physical characteristics controlling the probability and energy of rockfall, and the most important aspects of these have the following indicators:

- Colluvial slopes (loose, unconsolidated) with a substantial fraction of cobble or larger clasts upslope of critical values
- Slopes greater than 22° (40%) in areas of moderate to high soil burn severity
- Areas of past rockfall, flat surfaces along the base of slopes collect rockfall and can record the impacts of rocks (pavement, roads, trails, and tree strike)

Rockfall hazard treatments are extremely variable from placing K-rails or fencing to block off certain high hazard areas to installation of rockfall fencing and rock scaling. Again, temporary area closures are the fastest, easiest, and most cost-efficient way to mitigate rockfall.

Consider Treatment Alternatives Based on Road Type/Classification

Post-fire response should always start with the most important or highest-classification roads. For US rural transportation areas, three main types of roads exist as defined based on user comfort and what type of vehicles can access them. An example of a maintenance level classification system with treatment considerations is included below:

Maintenance Level 3 – High user comfort with design higher speeds, accommodates all vehicle types and will generally be asphalt roads.

- Storm inspection and response should be prioritized for these roads.
- For asphalt sections of level 3 roads, consider construct a super dip at stream crossings.
- Install natural (woody) or permanent (metal beam) trash racks, debris dams/deflectors, and check dams above culverts or major crossings, ideally accessible for cleanout by equipment.

Maintenance Level 2 – Moderate user comfort with moderate design speeds, accommodates most vehicle types and are usually categorized by aggregate surfacing.

- For stream crossings, remove head-wall section on low-gradient side and cut down as much as possible to reduce fill over the pipe and provide an armored overflow channel over the roadway and on the low-gradient side.
- Add rolling dips leading into culverts to move water and sediment off the road before the culvert.
- Remove roadside berms.
- Install custom relief pipes where possible, especially in larger fills where equipment isn't available to reduce fill. Relief pipes will be needed for 1-2 years post-fire and can be re-used from one fire to the next.
- Install natural (woody) or permanent (metal beam) trash racks, debris dams/deflectors, and check dams above culverts or major crossings, ideally accessible for cleanout by equipment.

Maintenance Level 1 – Low user comfort with slow design speeds, accommodates four-wheel drive vehicles with high clearance and provide limited access and are constructed out of native material.

- Out-slope (fill slope pull back) road when and where possible and stabilize with local rock found on site. Restore pre road construction conditions as much as possible, remove areas for water and sediment to collect. Collection of water and sediment on these roads can lead to larger failures and more work.
- Add rolling dips leading into culverts to move water and sediment off the road before the culvert.
- Remove roadside berms.