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The Cost-Effectiveness of Satellite Earth Observations to Inform a Post-Wildfire Response

Richard Bernknopf, Yusuke Kuwayama, Reily Gibson, Jessica Blakely, Bethany Mabee, T.J. Clifford, Brad Quayle, Justin Epting, Terry Hardy, and David Goodrich

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Authors

Richard Bernknopf: Department of Economics, University of New Mexico, 1915 Roma Avenue NE 1019, Albuquerque, NM 87131

Yusuke Kuwayama: Resources for the Future, 1616 P Street NW, Suite 600, Washington, DC 20036

Reily Gibson: Resources for the Future, 1616 P Street NW, Suite 600, Washington, DC 20036

Jessica Blakely: Resources for the Future, 1616 P Street NW, Suite 600, Washington, DC 20036

Bethany Mabee: Resources for the Future, 1616 P Street NW, Suite 600, Washington, DC 20036

T.J. Clifford: Bruneau Field Office, Bureau of Land Management, US Department of the Interior, 3948 Development Avenue, Boise, ID 83705

Brad Quayle: Geospatial Technology and Applications Center, Forest Service, US Department of Agriculture, 2222 West 2300 South, Salt Lake City, UT 84119

Justin Epting: Geospatial Technology and Applications Center, Forest Service, US Department of Agriculture, 2222 West 2300 South, Salt Lake City, UT 84119

Terry Hardy: Supervisor’s Office, Boise National Forest, Forest Service, US Department of Agriculture, 1249 S. Vinnell Way, Suite 200, Boise, ID 83709

David Goodrich: Southwest Watershed Research Center, Agricultural Research Service, US Department of Agriculture, 2000 East Allen Road, Tucson, AZ 85719

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Abstract

We use a value of information (VOI) approach to demonstrate the cost effectiveness of using satellite imagery as part of Burn Area Emergency Response (BAER), a federal program that identifies imminent post-wildfire threats to human life and safety, property, and critical natural or cultural resources. We compare the costs associated with the production of a Burn Area Reflectance Classification (BARC) map and implementation of a BAER response when imagery from satellites (either Landsat or a commercial satellite) is available to the costs of BARC map production and BAER response when the BAER team relies on information collected solely by aerial reconnaissance. The case study includes two evaluations with and without BARC products: (a) costs and cost savings for a specific wildfire incident request and (b) costs and cost savings of a multi-incident BARC map production program. In both cases, satellite imagery, and in particular, Landsat is the most cost-effective way to input burn severity information into the BAER program, with cost savings of up to $35 million over a five-year period.

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1. Introduction

Wildfires continue to affect human and natural systems well after they are contained. Over time, the reduced vegetative cover and altered soil properties that fires leave behind can lead to erosion, runoff, flooding, and sedimentation; threaten important water supplies; and make the land vulnerable to invasive species (Calkin et al. 2007; Lentile and Holden 2006; Morgan et al. 2014; Jones et al. 2017). To reduce damages due to these secondary effects within a forest and downstream, managers can take a number of immediate actions, including the following: (a) determine if an emergency condition like a landslide or reservoir contamination exists after a fire; (b) alleviate emergency conditions to help stabilize erosion-prone soil as well as control water, sediment, and debris movement; (c) prevent the destruction of ecosystems; (d) mitigate significant threats to health, safety, life, property, and downstream values-at-risk (VAR); and (e) monitor how emergency treatments are implemented and measure their efficacy (NPS 2018a).

When fires occur on public lands managed by the federal government, managers use a formal protocol developed by the US Forest Service (USFS; housed under the US Department of Agriculture, USDA) known as the Burn Area Emergency Response (BAER). The BAER program aims to identify imminent post-wildfire threats to human life and safety, property, and critical natural or cultural resources (NPS 2018b). A critical step in the BAER process is the identification, mapping, and field verification of the soil burn severity (i.e., SBS, the loss of organic matter in the soil and aboveground organic matter that is converted to ash [Keeley 2009]) within the fire perimeter by an assembled team of experts. The BAER team then recommends mitigation measures to help offset potential threats from secondary post-fire impacts. Over the past several decades, federal forest and land managers have used a variety of information sources to determine SBS in areas affected by wildfire. Understanding SBS in these areas can help managers prioritize post-wildfire response activities.

In this paper, we use a value of information (VOI) approach to demonstrate the cost-effectiveness of using satellite imagery as part of the BAER program assessment process. Specifically, we compare the costs associated with the production of a Burn Area Reflectance Classification (BARC) map and implementation of a BAER response when imagery from satellites (either Landsat or a commercial satellite) is available to the costs of BARC map production and BAER response when the BAER team relies on information collected solely by aerial reconnaissance. The case study includes two evaluations with and without BARC products: (a) costs and cost savings for a specific wildfire incident request, and (b) costs and cost savings for a multi-incident BARC map production program. In both cases, satellite imagery (in particular, Landsat) is the most cost-effective way to input burn severity information to the BAER program, with cost savings of up to $35 million over a five-year period.

1.1. Tools Used by Managers to Assess Burn Severity

1.1.1. Aerial Sketch Mapping

Historically, managers assessed burn severity by producing a manual sketch of the burned area on a topographic map. Burn severity sketches were developed using one of two methods: (a) ground-based surveys, or (b) ground-based surveys in conjunction with aerial surveys from low-flying aircraft or helicopters (Bobbe et al. 2003). However, manual sketch mapping presented several shortcomings to assessing burn severity. First, teams from the BAER program and other agencies used different methods to map burn severity. Second, due to time constraints that the BAER team operates under, field surveys conducted for large wildfires were often incomplete and only a small percentage of the burned areas could be sampled. Third, aerial surveys and sketch mapping were expensive. Fourth, there were risks associated with flying light aircraft in smoky conditions to conduct aerial surveys. Finally, manual sketch mapping results were subjective and biased because they relied on the experience and skill of the person performing the mapping (Bobbe et al. 2003). For large wildfires, multiple persons would typically be employed to perform the mapping, introducing additional variability and subjectivity in the final SBS map.

1.1.2. Airborne Digital Cameras

In the mid-1990s, the Remote Sensing Applications Center (under the USDA's Forest Service) and Kodak developed a color infrared digital camera that could be mounted on aircraft to acquire imagery and map an entire fire (Hardwick et al. 1997). This process for acquiring imagery, compositing, and interpreting the color infrared digital imagery was made available to BAER teams, providing an improvement over aerial sketch mapping. However, using imagery from airborne digital cameras for burn severity mapping has its own limitations. It is expensive to deploy aircraft to cover large geographic areas and the limited number of vendors that provide this support can create delays between orders for imagery and delivery. Additional complicating factors include delays related to image processing times, the significant information technology (IT) support required to process the large data sets these images produce, and images with more detail than managers need to map burn severity.

1.1.3. Satellite Imagery

In 1972, the US Department of the Interior (DOI), NASA, and the USDA developed and launched the first Earth observation satellite, known as the Earth Resources Technology Satellite—the predecessor to the Landsat satellites. Since 2008, Landsat has provided freely available imagery to the general public and is used routinely in many private and public sector applications including the BAER program.

1.2. The BAER Program

1.2.1. Authority and Scope

BAER is a component of post-fire emergency response activities that involves repairing or mitigating damages caused by fire suppression, post-fire rehabilitation, and long-term fire restoration. The annual Appropriation Act authorizes DOI and USDA to conduct emergency stabilization procedures through the BAER program. Specifically, this law provides for the use of Wildland Fire Management funds for necessary expenses for "emergency rehabilitation of burned-over National Forest System lands and water." Public Law No. 105-277, Section 323(a) (as amended by Public Law 109-54, Section 434) provides the USFS and DOI authority to enter into watershed restoration and enhancement agreements and expend appropriated funds on non-federal lands when there is a clear benefit to the National Forest System lands in the watershed. Forest Service Manual 2500 (USFS 2018) describes how the two agencies are specifically required to use the BAER protocol to do the following:

- Conduct assessments promptly on burned areas following wildfires larger than 500 acres to determine if a burned-area emergency exists;
- Undertake response actions or emergency stabilization when analysis shows that planned actions are likely to reduce risks within the first year following containment of the fire;
- Employ measures that provide sufficient protection at the least cost while meeting risk management objectives and emergency stabilization measures one year after fire containment; and
- Monitor emergency stabilization measures for up to three years from containment of the fire.

It is a statutory requirement that agencies complete the wildfire BAER report according to the timetable in USFS Manual Interim Directive 2520-2018-1 in order to qualify for emergency stabilization funds. Timing is based on the following requirements in Section 2523.06 of Chapter 2520—Watershed Protection and Management:

- Initial requests for BAER funding should be submitted to the Regional Forester within seven calendar days after total containment of the fire, unless special arrangements have been negotiated (Sec. 2521.04b).
- Regional responses to BAER funding requests (in the form of decisions or referral to Washington Office, Director of Watershed, Fish, Wildlife, Air, and Rare Plant Staff [WFW]) should be completed within three business days of receipt.
- Washington Office responses to BAER funding requests should be completed within three business days of receipt.

The BAER assessment protocol leads to the development of a post-wildfire emergency stabilization plan, which includes the collection of satellite imagery, creation of a BARC map for delivery to the BAER team, classification of SBS with field validation, definition of the emergency in the burned region, and implementation of treatments.

1.2.2. Assessment

BAER teams consider the severity of the burn, potential post-wildfire impacts, and response options, using satellite imagery to produce a BARC map. Once BAER team members have secured a BARC map, the assessment proceeds with the production of a field-verified SBS map to classify the fire's effect on ground surface characteristics, including char depth, organic matter loss, altered color and structure, and reduced infiltration (Parsons et al. 2010), which is field validated. Using the SBS map, the BAER team evaluates the magnitude of risk posed to each valuable resource within and downstream from the burned region and decides which actions will be most effective to mitigate these risks. Since the SBS map is the basis for the emergency stabilization plan submitted by the BAER team to the federal land manager, it is crucial that this tool accurately represent the fire's actual impact on soil conditions.

The current BAER assessment process used in our analysis as the reference case for the VOI impact assessment is dependent on Landsat imagery. Our retrospective analysis estimates the cost-effectiveness of using the Landsat imagery in the assessment for a specific incident: the 2013 Elk Complex Fire in the Boise National Forest of Idaho that burned 130,960 acres. We compare this reference case to a counterfactual case in which Landsat imagery is unavailable and inputs to the assessment are instead collected from helicopters and/or commercial satellite imagery. Although helicopters are used as the primary means for imagery in one of the counterfactual cases, they are employed for a variety of purposes in both the reference and counterfactual cases with varying intensities by a BAER team to generate burn severity classifications. In the reference case, we focus on the cost savings realized with the addition of Landsat imagery, which reduces the need for expenditures for commercial imagery or helicopters as the primary tool for data collection.

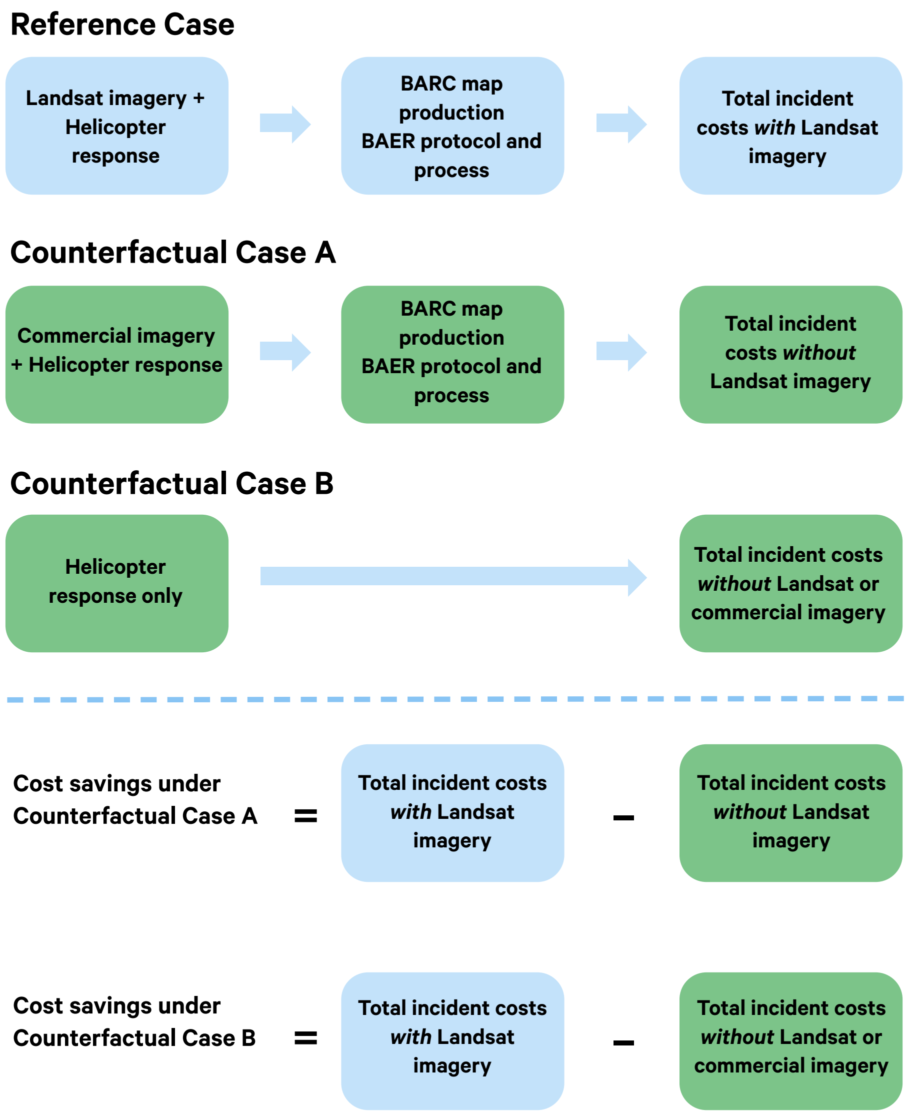
2. Assessing the Cost-Effectiveness of Landsat Imagery

In this VOI impact assessment, we estimate the cost-effectiveness of using Landsat satellite imagery as the basis for BARC map production and BAER protocol implementation. VOI is a microeconomic approach we use to determine what information is worth by assessing the difference in how people make a decision with the information (using Landsat imagery as the reference case) and without it (using commercial satellite imagery or no satellite input as the counterfactual cases). The VOI approach relies on the premise that information can influence decisionmaking; information is only meaningful in the presence of uncertainty and valuable when there is something at stake in a decision.

To quantify the value of additional information, we must consider its application in a specific decision context. In our evaluation, satellite imagery is potentially valuable because it may reduce the incident operational costs of producing a BARC map and implementing the BAER assessment protocol relative to the case in which the Landsat imagery is not available. Figure 1 illustrates how the costs of map production in the reference and counterfactual cases can be compared for the Elk Complex Fire case study.

Other studies have argued that Earth observations can greatly improve the speed, precision, and accuracy of post-fire mapping efforts (Parsons et al. 2010). Such improvements are likely to be cost-effective and are also likely to lead to better decisions. This analysis will focus primarily on quantifying the former, showing how using Landsat imagery to generate a BARC map reduces the cost of producing the SBS classification. We note that Landsat data can not only reduce map production costs—they may also help the BAER team produce a more consistent map with lower inherent variability, which can inform decisions that yield improved environmental and socioeconomic outcomes. However, in this analysis, we limit ourselves to quantifying the value of cost savings and leave the value of potentially improved environmental and socioeconomic outcomes for a future study. As such, the cost savings that we quantify in our study represent a lower bound on the socioeconomic benefits yielded by the use of satellite imagery in the BAER assessment.

Figure 1. Calculating Cost Savings Using the Reference Case and Counterfactual Cases



* The reference case is displayed in the blue boxes, and the counterfactual cases are represented by green boxes.

3. The BAER Protocol

A BAER team is assembled after a fire as soon as it is safely possible to complete fieldwork for a wildfire response. The team consists of individuals representing one or more of the following disciplines: safety, engineering, hydrology, minerals, geology, soils, cultural resources, wildlife, range management, vegetation, recreation, environmental compliance, documentation, and geographic information systems (GIS).[1] The team "prepare[s] an emergency rehabilitation and restoration plan," which involves assessing SBS and estimating "the likely future downstream impacts due to flooding, landslides, and soil erosion" (USFS n.d.). The USFS-Geospatial Technology and Applications Center (GTAC) provides derived products from Landsat and, when necessary, from commercial satellites to rapidly map BARC or changes between before the fire and after the fire (USFS n.d.). The BARC data are used as an input into the development of the final SBS map. An emergency stabilization plan is developed and a funding request for mitigation is based on cost-risk analysis (Calkin et al. 2007).

There are several responsibilities and activities involved in implementing an emergency stabilization plan. The team begins by verifying the BARC map with in-situ sampling to classify burn severity and then determines the fire's ecological impact and magnitude of risk to resources with an SBS classification.

If burn severity is high, there are likely to be long-lasting ecological impacts to the local and regional environment. Hydrological, biogeochemical, and microbial processes may be altered by the fire. Changes to these belowground processes have the potential to threaten the health and sustainability of aboveground human and natural systems (Lentile and Holden. 2006). Emergency response treatments may be necessary to stabilize these processes following a fire.

The SBS classification helps BAER team members identify and rank actions that should be taken to mitigate wildfire-associated risks. Assessments are usually completed within 5 to 10 days, depending on the size of the fire. Treatments and actions are done immediately to prevent or minimize additional damage. Typical treatments and activities include placing structures to slow soil and water movement, stabilizing soil, preventing contamination of surface water, stabilizing cultural sites and critical heritage resources, fencing off safety hazards, protecting critical species habitats, and minimizing the establishment of invasive species (NPS 2018a). The BAER process is described below in three stages: VAR Identification, BARC development, and SBS mapping.

1 The US Bureau of Land Management (BLM) national BAER teams also include a hydrologic modeling specialist who is competent in using the AGWA (Automated Geospatial Watershed Assessment; Goodrich et al. 2012) watershed modeling tool that provides consistent estimates of the relative changes in runoff volume, peak runoff rate, erosion, and sediment yield from the pre-fire to post-fire conditions for a range of precipitation levels.

3.1. VAR Identification

To plan mitigation actions for post-fire impacts, the BAER team must first identify and quantify the VAR in the post-fire environment. VAR is defined as the values or resources that are at risk of damage or loss. Risk is determined by the probability of damage and the magnitude of consequences if damage occurs (Calkin et al. 2011). The team must determine where important resources are located relative to the burned area and predict how the fire's secondary effects may threaten these values. Resources at risk can include archeological artifacts, historic buildings, water quality, animal and plant habitats, bridges, buildings, roads, culverts, timber, and use and access to commercial activities (Calkin et al. 2007). It is from these estimations and predictions regarding post-fire effects that the BAER team forms expectations for various actions and plans an emergency response.

3.2. BARC Development

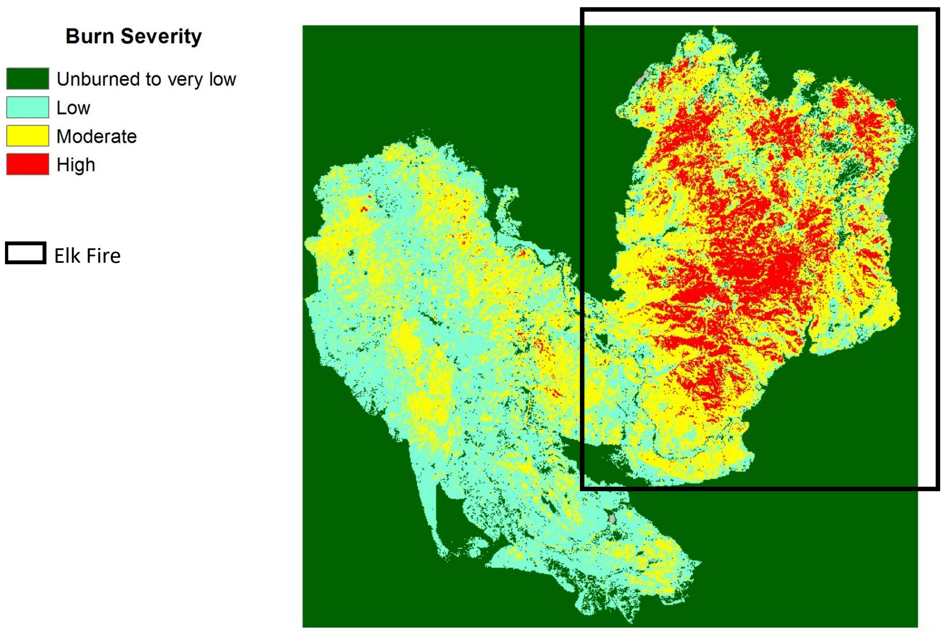
The use of satellite imagery helps inform the BAER team and the post-fire response process. Landsat imagery delivers comprehensive pre-fire land cover and post-fire land cover changes on the BARC map to become an input to the SBS mapmaking process (Hudak et al. 2004). Landsat images are terrain-corrected and georeferenced so they can be readily imported into GIS and the AGWA watershed modeling tool. Figure 2 illustrates the BARC product that was developed for the Elk Complex wildfire, which is based on Landsat imagery and is the subject of our cost-effectiveness analysis.

Burn severity is inferred from observed changes in the post-fire appearance of vegetation and soil (Robichaud and Ashmun 2013). Radiometers are used to passively measure the reflection of electromagnetic radiation from surfaces across the burned landscape. In particular, the Landsat Thematic Mapper sensor radiometers are sensitive to six bands on the electromagnetic spectrum (Lentile and Holden 2006). Near-infrared bands are reflected by green, healthy vegetation; mid-infrared bands are reflected by rock and bare soil. In areas where infrared values captured by Landsat are high, the landscape is likely bare, rocky, or charred. This means that areas where post-fire satellite imagery shows the largest increase in infrared values are likely to be the most severely burned (Parsons et al. 2010).

Pre- and post-fire Landsat satellite images of a burn region have been used to generate BARC maps since 2002 (Robichaud and Ashmun 2013). The differenced Normalized Burn Ratio (dNBR) is used to detect changes between the pre-fire and post-fire infrared band values (Parsons et al. 2010). Since burn severity cannot be expressed by a single quantitative measure, observed changes are grouped into classes (Lentile and Holden 2006). These classifications range from “unburned” to “high severity” and are integrated into a BARC map.

The initial BARC map values alone are not a good fit for the observed burn. Field observations are undertaken to verify and to make subsequent adjustments to the map to create classifications that accurately reflect the spatial severity of the burn. These spatial patterns are observed at specific land coordinates and then overlaid onto the BARC map to determine the accuracy of the classifications. If the BAER team identifies values that are not properly classified, it uses the patterns observed to adjust the BARC threshold values for the entire burned area through systematic editing.

Figure 2. BARC Map of the Elk Complex Wildfire (depicted by area outlined in black) in the Boise National Forest



Source: Epting, Justin via USGS Earth Resources Observation and Science (EROS) Center. 2019. Personal communication between Justin Epting, USFS GTAC and Richard Bernknopf, University of New Mexico. May 9.

At times, localized editing may also be necessary depending on the quality of the satellite imagery. Smoke and clouds may block out a portion of the burned area or complex topography may create inconsistencies in the BARC map (Parsons et al. 2010). In these cases, the BAER team may need to perform more extensive aerial or field observations to classify SBS. Only after the BARC map has been verified or adjusted to reflect the in-situ soil conditions can it be called an SBS map and used by the BAER team to inform the emergency stabilization plan.

A BARC product is typically generated once for every incident where a BAER team submits a request. However, for long-duration incidents, multiple iterations of BARC products may be generated at the request of BAER teams.

3.3. SBS Mapping

SBS is a classification that indicates the ecological impact of a fire on the burned region. A low rating means that the soil will require little to no maintenance; a high rating means that the soil exhibits unfavorable properties and will require extra maintenance or costly alterations (Clifford 2013). Table 1 lists characteristics of SBS for low, moderate, and high levels. The SBS map helps team members understand the wildfire's primary effects so that they can form expectations about the secondary effects. Once VAR are georeferenced, BAER team members can estimate the burn impact on VAR in a particular area. The team uses additional decision support tools to assess secondary fire effects. For example, the AGWA modeling tool simulates watershed runoff and erosion responses in the post-fire environment and can provide a quick visual indication of watershed "hot spots" (Goodrich et al. 2012). Because AGWA uses information contained in the SBS map, the accuracy of the AGWA model is dependent on the accuracy of the SBS map.

Using the SBS map, the BAER team evaluates the magnitude of risk posed to each valuable resource and decides which actions will be most effective to mitigate those risks. During the response, a geospatial BAER team member will integrate and digitize the collected data from all data sources available to generate the SBS map for the whole burned region. As mentioned above, the initial imagery or sketches can come from a variety of sources but the map must be field validated for it to be called an SBS map.[2]

2 The AGWA model needs observations of pre- and post-fire rainfall, runoff, and erosion to be properly calibrated. With them, the resulting model estimates cannot be expected to closely predict actual runoff and erosion. Therefore, large relative changes between the pre- and post-fire modeled watershed response are the primary metric to identify "hot spots."

Table 1. Summary of SBS Class Factors

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

* MDI: Mini-disc infiltrometer
Source: Parsons et al. 2010 (Appendix E).

4. Case Study: Elk Complex Fire, Boise National Forest

In early August 2013, lightning strikes ignited a fire that blazed through the Boise National Forest in Idaho and swept into neighboring mountain towns. By the time the fire was declared 100 percent contained on August 31 of that year, it had burned 180,960 acres. Nearly 75 percent of the burned area exhibited high to moderate burn severity. The BAER team for the Elk Complex Fire consisted of 30 individuals and was assembled between August 21 and 24 (Hamilton 2013).

4.1. BARC Map Production Costs

4.1.1. Reference Case (R): Landsat Imagery and Helicopter Response

The team designed and implemented an emergency stabilization plan using core data derived from Landsat. GTAC obtained pre- and post-fire images from Landsat 7 on August 17, 2013, and created the BARC map (Clifford 2013). The final SBS map classified 33,285 acres as high burn severity, 63,022 acres as moderate burn severity, and 26,845 acres as low burn severity. Using these classifications, the BAER team was able to rate VAR and prioritize response actions. In the emergency stabilization plan that was submitted on September 9, resource assessments for soil, hydrology, vegetation, wildlife, and fisheries were all directly informed by the SBS map (Clifford 2013).

Using a BARC, the BAER team identified about 16,000 acres within the burned watersheds that had high burn severity and steep slopes. These acres were considered treatable because they were not likely to recover naturally and were located within a range of hillslope gradient that had been successfully treated after past fires in the area. The BAER team also used the AGWA tool to simulate the watershed response for pre-fire and post-fire conditions to identify areas at high risk for runoff and erosion. The group assessed the treatable area, field observations, professional judgment from the multidisciplinary BAER team members, and the spatial results from AGWA to target seed and mulch treatments in areas that most effectively reduced the threats. Specifically, the BAER team was able to narrow down the 16,000 acres originally considered treatable to between 2,000 and 4,000 acres for priority mitigation.

The pre-fire conditions of vegetation as well as pre-fire measurements of ground fuels, litter, and duff are key factors that help illustrate the general land attributes and spatial heterogeneity of vulnerable areas in a forest. Figure 3 is a pre-fire map showing an outline of the area burned by the 2013 Elk Forest component of the larger Elk Complex Fire. It shows pre-fire locations (such as hillsides with patches of dense vegetation) vulnerable to becoming an area with high SBS after a fire.

Before a wildfire, areas with low-surface vegetation biomass will have low values of near-infrared reflectance in remote sensing imagery (Parsons et al. 2010). When a wildfire occurs and burns areas with low biomass, the changes are not substantial to the satellite sensor—these areas are thus often classified correctly in the BARC process as having low SBS. This may be an appropriate classification when assessing only the soil and ground conditions. However, if the BARC (and its source data, the dNBR) is used to help map vegetation effects, it may underestimate the vegetative burn severity. In the case of the Elk Complex Fire, the BAER team conducted field observations with helicopter support to make necessary adjustments to the map to create the BAER burn severity map for the Elk Forest component of the fire (Figure 4). The spatial patterns in the BARC map in Figure 2 and the field verification were combined to determine the most accurate SBS classifications. BAER teams adjust the BARC threshold values for the entire burned area through systematic editing.

Figure 3. Pre-fire Map of the 2013 Elk Forest component of the Elk Complex Fire in the Boise National Forest (Idaho)

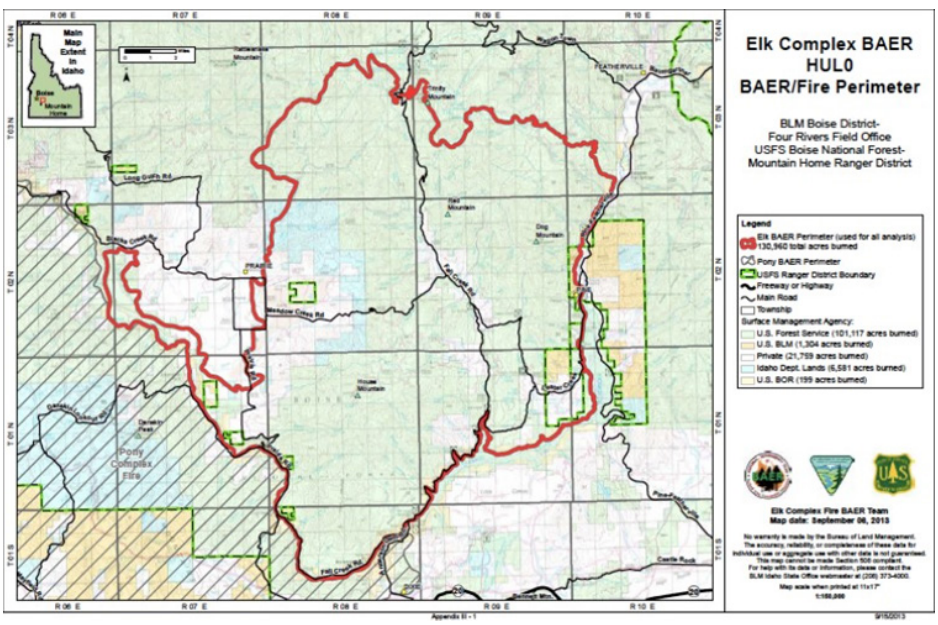


Figure 4. Soil Burn Severity Map of the 2013 Elk Forest component of the Elk Complex Fire in the Boise National Forest (Idaho)

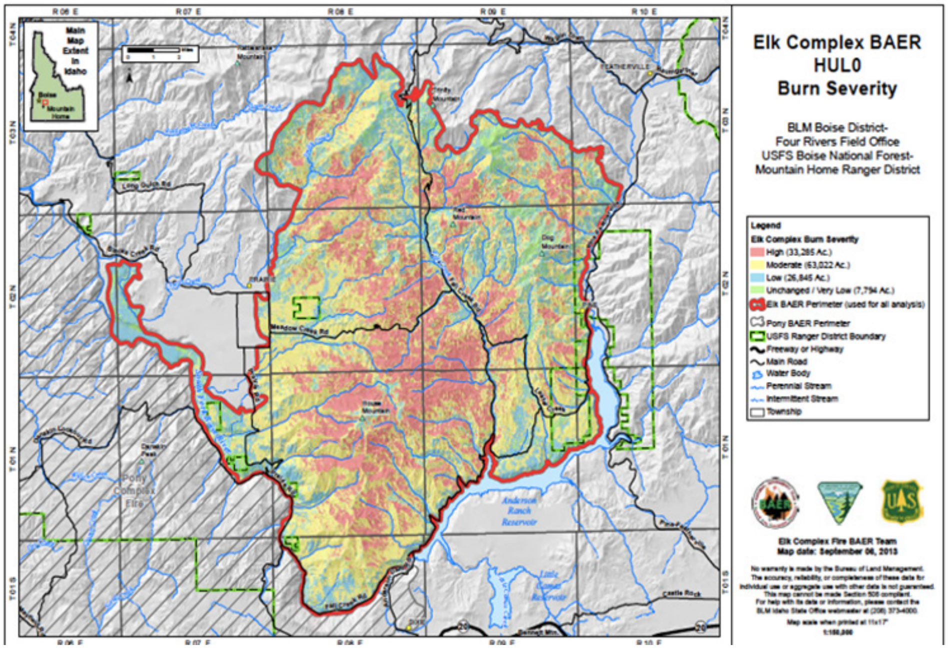


Table 2. BARC Production Cost per individual Wildfire Incident Request

	Landsat imagery (1)	Commercial imagery (2)
Analyst Labor	$365–$480	$365–$480
Hardware	$2.93	$2.93
Software	$75.57	$75.57
Satellite Imagery	$0	$500–$1,000
Total cost for individual BARC	**$443.50–$558.50**	**$943.50–$1,558.50**

[1] Estimated to be 7–8 hours per incident but varies by incident. Does not include variable associated costs for IT support (i.e., network storage, maintenance and support for computing hardware, network, and relevant IT tools).
[2] Assumes 150 BARC requests received by the USFS over a year ($440 per 150 requests).
[3] Annual USFS cost of $11,335 for software licenses for ERDAS Imagine and ESRI ArcGIScenses.
Source: Epting, Justin and Brad Quayle. 2018. Personal communication between Justin Epting, USFS GTAC; Brad Quayle, USFS GTAC; and Richard Bernknopf, University of New Mexico. November 13.

We obtained information on BARC production costs from a history of operational wildfire incidents provided by GTAC. The costs listed in Table 2 were derived from discussions with GTAC staff regarding BARC production costs associated with a wildfire incident request. Column 1 lists production costs incurred in our reference case (i.e., when Landsat imagery is used). The major cost component is tied to an analyst's labor, which (in our estimates) is based on a typical request to generate a BARC product and provide related support activities to a BAER team. Typical analyst activities include: communicating and consulting initially with the BAER team leader; tracking and coordinating support requested from the BAER team; acquiring satellite imagery; preprocessing satellite imagery; conducting BARC mapping; creating imagery and related products for delivery; providing follow-up communications and technical support to the BAER team; and conducting SBS map and data retrieval for the BAER team as well as preparing for website dissemination. When satellite imagery is used, a GIS expert on a BAER team can employ a "slider bar" approach to recalibrate the BARC in a digital image in order to illustrate the differencing between pre- and post-fire conditions. Hardware and software costs are low. Landsat imagery (that is both terrain-corrected and georeferenced) is available at no cost from the Multi-Resolution Land Characteristics (MRLC) consortium.

4.1.2. Counterfactual Cases: (A) Commercial Imagery and Helicopter Response; (B) Helicopter Response Only

Our counterfactual cases assume that Landsat imagery is not available and that the BAER teams find ways to create BARC and SBS maps comparable to those produced when Landsat imagery is available.

The first counterfactual case is a commercial purchase of a single Landsat scene-equivalent (for production costs associated with this case, see Table 2, Column 2). Costs are similar to those for when Landsat imagery is available (Table 2, Column 1), except for a fee-per-scene of $500 for commercial satellite imagery. If existing and suitable pre-fire imagery was not in the MRLC archive or in the Landsat imagery provided by the USGS, two scenes may be required for purchase. The second counterfactual case is a BAER protocol that involves only helicopters and is performed exclusively by the BAER team. Video footage is collected, processed, and georeferenced to map SBS. In this case, the fire is divided into zones—the team locates itself at high points and draws on maps with colored pencils. This process requires someone to digitize these drawings by hand for suitable input to GIS, a task that can be time consuming when on deadline for creating an SBS map.

4.2. BAER Costs

A BAER assessment has different costs depending on whether a BARC map is available for support following a wildfire incident. Fire attributes (such as ease of access, availability of high point vistas, vegetation, topography, fire size, aspect, and shadows reflecting the time of day or sun angle) can cause significant variations in the cost of a BAER assessment. Costs vary additionally depending on what information is initially available (e.g., from a BARC map or pre-fire AGWA model run). The BAER team may divide work into sections or begin observations in one area while other parts of the fire are still burning.

Data used by the BAER team are associated with some uncertainty. The BARC map has an approximate 30-meter spatial resolution of the whole burn area. If the BAER team manually sketches the map from field observations, it is likely that there will be many pockets of burned or unburned areas that are not captured by that work. These uncertainties impact the accuracy of the AGWA simulation and the response decisions made by the BAER team. When the BAER team does not have the BARC map, they may take several actions to generate a similar SBS map. In this circumstance, sketches and/or aerial observations from the field are registered and plotted on a high-resolution topographic map from various vantage points.

Similar to our estimate of the costs of producing a BARC map, in partnership with BLM and USFS staff, we developed estimates of the BAER assessment costs for the reference and counterfactual cases in this analysis. Table 3 lists the cost categories as well as amounts for developing and using an SBS map with satellite imagery from Landsat, commercial satellites, or helicopters (i.e., aerial imagery). BAER cost categories (although similar across BAER assessments but unlike the BARC production process) have several complexities because the unit cost of assessment tasks varies with fire size and/or VAR.

Some tasks can be assessed regardless of whether or not a BARC map is available. BAER teams assign work units that are a function of the total number of hours associated with a task. For example, for the SBS validation, the task unit required amounts to a quantity of person-hour-days of fieldwork equal to 16 persons × 14 hours × 2 days. The unit cost for a task also varies by fire size based on the following breakouts: 0–30,000 acres, 30,000–200,000 acres, and greater than 200,000 acres). For the Elk Complex Fire, the personnel cost is based on a fire size of 130,960 acres. We assume that a task is accomplished by an employee at the GS-11 level of the federal government pay scale at a cost of $60.16 per hour for 2,088 hours in a year. This cost includes salary, benefits (35 percent of salary), and facilities and administrative costs (52 percent of salary).

Table 3. BAER Protocols and Process Costs for the Elk Complex Fire

General Task	Resource	Units	Reference case (R) Landsat imagery and helicopter response*			Counterfactual case (A) Commercial imagery and helicopter response*			Counterfactual case (B) Helicopter response* only		
			Qty.	$/Unit	Total	Qty.	$/Unit	Total	Qty.	$/Unit	Total
Meet with incident management team	Persons	Hours	5	$60.16	$301	5	$60.16	$301	10	$60.16	$602
Gather paper maps for flight	Persons	Hours	0	$60.16	$-	0	$60.16	$-	2	$60.16	$120
Gather paper maps for field data collection	Persons	Hours	0	$60.16	$-	0	$60.16	$-	2	$60.16	$120
Load electronic maps on devices	Persons	Hours	2	$60.16	$120	2	$60.16	$120	0	$60.16	$-
Acquire BARC	Persons	Hours	1	$60.16	$60.16	1	$60.16	$60.16	0	$60.16	$-
Load BARC onto devices	Persons	Hours	2	$60.16	$120	0	$60.16	$-	0	$60.16	$-
Print BARC onto paper maps	Persons	Hours	1	$60.16	$60.16	0	$60.16	$-	4	$60.16	$241
Fieldwork for severity validation	Persons	Hours	112	$60.16	$6,738	168	$60.16	$10,107	448	$60.16	$26,952
Helicopter mapping	Persons	Hours	16	$60.16	$963	32	$60.16	$1,925	64	$60.16	$3,850
Helocopter video and photo processing	Persons	Hours	8	$60.16	$481	32	$60.16	$1,925	24	$60.16	$1,444
GIS processing from field/helicopter to final SBS	Persons	Hours	8	$60.16	$481	16	$60.16	$963	72	$60.16	$4,332
GIS processing from BARC to final SBS	Persons	Hours	8	$60.16	$481	6	$60.16	$261	0		$-
Helicopter use (pilot, fuel, truck driver)	Persons	Hours	4	$300	$1,200	8	$300	$2,400	16	$300	$4,800
Helicopter fuel	Fuel	Hours of Fuel	4	$500	$2,000	8	$500	$4,000	16	$500	$8,000
Helicopter contractual use (cost)	Availability	Days	0.5	$3,000	$$1,500	1	$3,000	$3,000	2	$3,000	$6,000
Total			**171.5**	**$4,400**	**$14,505**	**279**	**$4,400**	**$25,162**	**660**	**$4,350**	**$66,481**

* Helicopter response involves costs associated with a pilot, fuel, fuel-truck driver, and mechanic. A helicopter day = 14 hours.
Source: Clifford, T.J. 2018. Personal communication between T.J. Clifford, BLM and Richard Bernknopf, University of New Mexico. October 1.

For all alternatives, fieldwork to validate SBS is the same. However, options where satellite imagery can be used include aid from electronic devices (e.g., tablets) that requires less GIS processing than previously needed with paper sketches. Using an electronic device requires less post-flight GIS processing regardless of whether helicopter-based mapping or satellite imagery is used. However, helicopter mapping requires more time in the air collecting images (photographs or video) and a substantial amount of time translating collected images into a preliminary estimate of SBS. The additional cost is reflected in the last column of Table 3 (row representing fieldwork for severity validation). Prior to the availability of multispectral cameras, interpretations were based on visual differences in photography. This particular step is time consuming and can delay access to images acquired from helicopters. After the images are translated, field validation can occur. It is at this point in the process that the field validation efforts are similar to those utilized for satellite imagery.

Table 4. Estimated Total Incident Cost and Savings for the Elk Complex Fire

	Reference case (R) Landsat imagery and helicopter response*	Counterfactual case (A) Commercial imagery and helicopter response*	Counterfactual case (B) Helicopter response* only
BARC map production	$443.50 to $558.50	$943.50 to $1,558.50	N/A
BAER protocol and process	$14,505.00	$25,162.00	$66,48100
Total	$14,948.50 to $15,063.50	$26,105.50 to $26,720.50	$66,481.00

Cost comparison of reference and counterfactual alternatives

Savings (B–R)	$51,418.00 to $51,532.50
Savings (B–A)	$39,760.50 to $40,375.50
Savings (A–R)	$11,157.00 to $11,657.00

4.3. Difference in Total Costs: Reference and Counterfactual Cases

4.3.1. Cost Savings per Incident

Savings realized under the BAER protocol when Landsat imagery is available to the BAER team (i.e., our reference case), relative to scenarios in which Landsat imagery is not available (i.e., our counterfactual cases), are given by the differences in the totals in the last row of Table 3. The total savings, which include costs for both

BARC map production and the BAER protocol, are shown in Table 4. The reference case is associated with per-incident savings that range between $11,157 (using commercial satellite imagery and helicopter response) and $51,418 (using helicopter response only).

4.3.2. Multi-year Cost Savings

In busy years, GTAC may receive 125 to 150 USFS BARC requests from BAER teams. Based on the cost savings per incident (see Table 4), we estimate the savings of using Landsat imagery for BARC map production and BAER response over a five-year period. For this estimate, we assume that there are 150 incident requests per year for BARC products and that the wildfires are of the same size and complexity as the Elk Complex Fire. Based on GTAC historical data, we assume that two scenes are acquired for a BARC request (pre- and post-fire). There are no significant economies of scale to savings in aggregating from an individual incident request to an annual rate of 150 requests. Cost savings are initiated in the first year following the investment. Our estimate assumes that the hardware cost is a one-time investment in the initial year of the program and that operating costs are incurred during years one through five.

For counterfactual case A (commercial imagery and helicopter response), assuming an initial investment cost in a computer of $2,200, the operating cost savings per year for 150 incident requests range from $1.7 million to $1.8 million, depending on whether the low or high cost estimates are used for Landsat and commercial satellite imagery. The present value of the cost savings from using commercial imagery instead of Landsat imagery for the five-year investment period ranges between $7.5 million and $8 million, assuming a 3.5 percent social discount rate.

For counterfactual case B (helicopter response only), the operating cost savings per year for 150 incident requests is $7.7 million. Thus, the present value of the cost savings from using Landsat imagery instead of a helicopter-only response for the five-year investment period amounts to approximately $35 million (again assuming a 3.5 percent social discount rate).

5. Conclusion

In this study, we demonstrate that BARC is a cost-effective input to wildfire management and post-fire mitigation assessments. We document the costs for a reference case in which the production of a BARC map and its use in the BAER protocol take place when Landsat imagery is available. We compare the costs in our reference case to costs that are incurred in counterfactual cases (in which Landsat imagery is not available). The counterfactual cases rely on data from a combination of commercial satellite imagery and helicopter response or on helicopter-only response in order to collect the information that would have been obtained from Landsat imagery. On a per-incident basis, both Landsat and commercial satellite data inputs are more cost-effective than the helicopter-only alternative. The reference case of an operational Landsat input into a BARC map is the most cost-effective alternative.

While this study demonstrates the cost savings of using Earth observations in post-wildfire response, it does not quantify the potential benefits of using satellite imagery in the form of improved information that can allow BAER teams to achieve greater protection of human life and safety, property, and critical natural or cultural resources. To the extent that satellite imagery provides information of superior quality relative to a helicopter-only response and may yield improved socioeconomic outcomes through the BAER protocol, the cost savings we quantify are only one component of the benefits of satellite imagery in this decision context. Future research could seek to quantify these additional benefits and thus help complete the picture regarding the full value of Earth observations in post-wildfire management.

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