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Monetising the savings of remotely sensed data and information in Burn Area Emergency Response (BAER) wildfire assessment

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Abstract. We used a value of information approach to demonstrate the cost-effectiveness of using satellite imagery as part of the Burn Area Emergency Response (BAER), a US federal program that identifies imminent post-wildfire threats to human life and safety, property and critical natural or cultural resources. We compared the costs associated with producing a Burn Area Reflectance Classification map and implementing a BAER when imagery from satellites (either Landsat or a commercial satellite) was available to when the response team relied on information collected solely by aerial reconnaissance. The case study included two evaluations with and without Burn Area Reflectance Classification products: (a) savings of up to US$51 000 for the Elk Complex wildfire incident request and (b) savings of a multi-incident map production program. Landsat is the most cost-effective way to input burn severity information into the BAER program, with savings of up to US$35 million over a 5-year period.

Keywords: cost effectiveness, fire economics, fire severity, policy, remote sensing.

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Introduction

Wildfires have been part of natural succession for years. Low-intensity fires promote biodiversity, reduce the risk of catastrophic fire, and can help some species reproduce. At the same time, 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 damage due to these secondary effects within a forest and downstream, several immediate actions are undertaken, including the following: (a) determining if an emergency condition such as a landslide or reservoir contamination exists; (b) alleviating emergency conditions to help stabilise erosion-prone soil as well as control water, sediment and debris movement; (c) preventing the destruction of ecosystems; (d) mitigating significant threats to health, safety, life, property and downstream values-at-risk (VAR); and (e) monitoring how emergency treatments are implemented and measuring their efficacy (NPS 2018*a*).

When fires occur on public lands managed by the federal government, a formal protocol is used, known as the Burn Area Emergency Response (BAER) developed by the US Forestry Service (USFS) in the US Department of Agriculture (USDA) and the US Bureau of Land Management in the US Department of Interior (USDOI). The BAER program aims to identify imminent post-wildfire threats to human life and safety, property and critical natural or cultural resources (NPS 2018*b*). A critical step in the BAER process requires a team of experts to identify, map and field-verify the soil burn severity (SBS), which is the loss of organic matter in the soil and aboveground organic matter that is converted to ash (Keeley 2009). The BAER team then recommends mitigation measures to help offset potential threats from secondary post-fire effects. Over the past several decades, federal forest and land managers have used a variety of information sources to determine the SBS in areas affected by wildfire. Understanding the SBS in these areas can help managers prioritise post-wildfire response activities.

There are a variety of platforms that provide remotely sensed data, including high or midlevel resolution satellite imagery and aircraft.[1] The data also can be gathered directly in the field. We used a value of information (VOI) approach to demonstrate the cost-effectiveness of using satellite imagery as part of the assessment process in the BAER program. Satellite imagery is an investment in efficiency for conducting the BAER protocol and reconnaissance (USDA–USDI 2014). We used a cost-effectiveness evaluation to estimate the lowest cost for producing a wildfire response map (Nas 1996). Specifically, we compared the costs associated with producing an intermediate product in the BAER response called a Burn Area Reflectance Classification (BARC) map when imagery from satellites (either Landsat or a commercial satellite verified *in-situ* by helicopters) is available to the costs of map production when the BAER team relies on information collected solely by aerial reconnaissance.[2]

The case study included two evaluations with and without BARC products: (a) specific operating costs and savings of US\$11 000 to greater than US\$51 000 for a specific wildfire, the Idaho Elk Complex Fire incident request, and (b) investment and operating costs and savings with savings of up to US\$35 million over a 5-year period 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 into the BAER program.

This study retroactively assessed whether the USFS' decision to switch from the historical helicopter-only response to using midlevel resolution satellite imagery was cost-effective as the law mandates. It is the first analysis to demonstrate that USFS' decision to acquire Landsat imagery to implement the BAER program, established in the *Agriculture Act* of 2014, was cost effective. This study applied a cost-effectiveness measure that is one of the foundations of policy analysis (Green and Zeckhauser 2019) to the essential question of how the USFS should assure its capability for a time-dependent response to coordinate and prioritise mitigation and restoration following a wildland fire. Midlevel resolution imagery fits the activities required for a time-dependent effort such as the BAER process, which requires an operational source of information. At this level of resolution, publicly provided imagery is the least costly option, although a counterfactual is possible. Although commercial imagery and aerial reconnaissance imagery are available at more detailed resolution, they must be purchased and integrated into the existing government software, which adds a cost because either vendors will need to adjust their product or the government must.

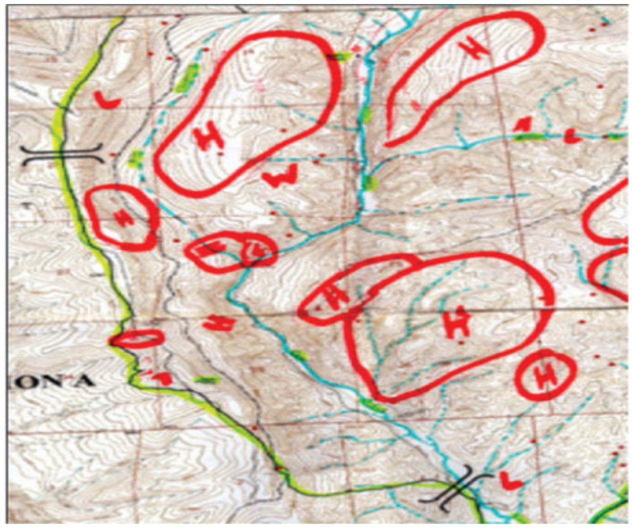

Fig. 1. Representative manual sketch map of a burned area. Source: pers. comm. between Brad Quayle, USDA Forest Service and Richard Bernknopf, University of New Mexico, 6 May 2020.

Tools used by managers to assess burn severity

Remote sensing has not always been part of the BAER process. Historically, managers assessed burn severity by producing a manual sketch of the burned area on a topographic map. Fig. 1 is a representative manual sketch map of a burned area. Areas circled in red are polygons of high or low burn severity (labelled 'H' and 'L'). Burn severity sketches were developed using either ground-based surveys or ground-based surveys in conjunction with aerial surveys from low-flying aircraft or helicopters (Bobbe *et al.* 2003). An improvement over sketch mapping was developed in the mid-1990s and made available to BAER teams: a colour infrared digital camera that could be mounted on aircraft to acquire imagery and map an entire fire (Hardwick *et al.* 1997). However, using imagery from airborne digital cameras for burn severity mapping had its own limitations. Realising that there were potential applications to use remote sensing in the BAER process, feasibility studies were conducted in late 1990s

[1]As an example, MODIS and the Sentinel constellation are both sources of midlevel resolution satellite imagery. Examples of sources of high-level resolution satellite imagery include DigitalGlobe's WorldView-2 and WorldView-3. Aircraft are typically the source of lidar.

[2]Because mid-resolution Landsat imagery is used for a variety of societal or market decisions, economists consider it a public good or general information (Bernknopf *et al.* 2020). As is the case with most general information, consuming Landsat imagery by using it to inform the BAER process does not subtract from any other individual's consumption of Landsat imagery for a different purpose (Mas-Colell *et al.* 1995; Varian 2003). By contrast, commercial imagery provides a private good that is defined as specific information (Bernknopf *et al.* 1993). In particular circumstances, remotely sensed data and information (RSDI) is collected by contractual or license agreement (e.g. WorldView-2 or WorldView-3 by DigitalGlobe) to deliver specific, high spatial resolution observations (Scott 2014). This RSDI is available in the marketplace and has been collected for a specific purpose only of concern to a particular user.

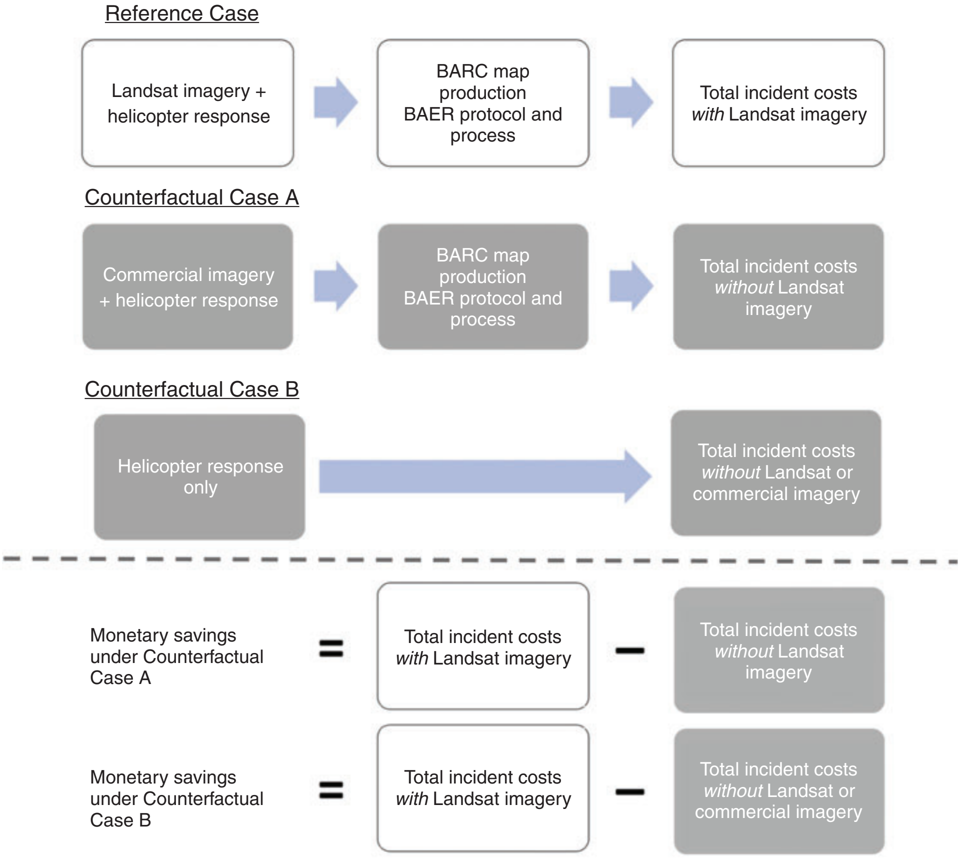

Fig. 2. Calculating monetary savings using the reference case and counterfactual cases. The reference case is displayed in the white boxes and the counterfactual cases are represented by grey boxes.

with airborne photography and operational satellite support started in 2001.

This decision was based on the benefits that satellite imagery provides to the BAER program. Satellite information increases the BAER team's safety by reducing how much time the team spends in the field conducting helicopter surveys and ground reconnaissance. It helps the team focus on burned areas of high concern, allowing more time to analyse data and determine appropriate mitigation strategies. Satellite imagery yields better maps and more accurate, precise SBS estimates to facilitate geospatial analysis and modelling. Since 2008, Landsat has provided freely available imagery to the general public and is used in many private and public sector applications, including the BAER program.[3] There is no comparable midlevel resolution commercial imagery that could be used to implement the BAER protocol without modifications, which increases costs.

The BAER program: authority and scope

BAER is a component of post-fire emergency response activities that involve repairing or mitigating damage caused by fire suppression, post-fire rehabilitation and long-term fire restoration. The annual *Appropriation Act* authorises the USDA and USDOI to conduct emergency stabilisation 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.' As amended by Public Law 109-54, Section 434, Public Law No. 105-277, Section 323(a) provides the USDA and USDOI 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. The Forest Service Manual 2500 (USFS 2018) describes how the two agencies are specifically required to use the BAER protocol, outlining geographic, temporal and cost considerations that must be met. 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 stabilisation funds. Timing is based on requirements in Section 2523.06 of

[3]The Geospatial Technology and Applications Center uses satellite imagery to create the BARC map for the BAER team. The map provides the BAER team with the initial information for SBS, a sample of which then needs to be verified in the field using helicopters to create the final SBS map. So, the satellite does the reconnaissance of SBS using spectral imagery instead of using helicopters to do the same thing. This is what makes satellite imagery more cost-effective for the BAER process.

Chapter 2520 – Watershed Protection and Management and Section 2521.04b.

The BAER assessment process

BAER teams consider the severity of the burn, potential post-wildfire effects and response options, using satellite imagery to produce a BARC map. Once a BARC map is secured, 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 colour and structure and reduced infiltration (Parsons *et al.* 2010). 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. Because the SBS map is the basis for the emergency stabilisation plan submitted to the federal land manager, it is crucial that this tool accurately represent the fire's actual effect on soil conditions.

The current BAER assessment process, which depends on Landsat imagery, is the reference case for the VOI impact assessment. This retrospective analysis was an estimate of the cost-effectiveness of using Landsat imagery in a specific incident: the 2013 Elk Complex Fire in the Boise National Forest of Idaho that burned 73 232 ha, of which 52 998 ha were within the Elk portion of the complex. The Elk portion of the fire was the focus of our analysis. We compared this reference case to a counterfactual case in which Landsat imagery was unavailable and inputs to the assessment were collected from helicopters and/or commercial satellite imagery. Although helicopters were used as the primary means for imagery in one of the counterfactual cases, they were used for a variety of purposes in both the reference and counterfactual cases with varying intensities to generate burn severity classifications. In the reference case, we focused on the cost savings realised with the addition of Landsat imagery, which reduced the need for expenditure on commercial imagery or helicopters as the primary tool for data collection.

Assessing the cost-effectiveness of Landsat imagery

In this VOI impact assessment, we estimated the cost-effectiveness of using Landsat satellite imagery as the basis for BARC map production and BAER protocol implementation. VOI is a microeconomic approach to determining what information is worth by assessing the difference in how people make a decision with the information (using Landsat imagery as the reference) 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 decision-making; information is only meaningful in the presence of uncertainty and valuable when there is something at stake in a decision (Bernknopf *et al.* 2020).

To quantify the VOI, 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.

Fig. 2 illustrates how the costs of map production in the reference and counterfactual cases were 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 focused primarily on quantifying the former, showing how using Landsat imagery to generate a BARC map reduced the cost of SBS classification. We note that Landsat data can not only reduce map production costs, it 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 limited ourselves to quantifying the value of savings and left the value of potentially improved environmental and socioeconomic outcomes for a future study. As such, the monetary savings that we quantify in our study represent a lower boundary of the savings from using satellite imagery in the BAER process.

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 '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 2019). 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 and after the fire (USFS 2019). The BARC data are used as an input into the development of the final SBS map. An emergency stabilisation 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 stabilisation plan. The team begins by verifying the BARC map with *in-situ* sampling to classify burn severity and then determines the fire's ecological effect and magnitude of risk to resources with an SBS classification.

If burn severity is high, there are likely to be long-lasting ecological effects to the local and regional environments. Hydrological, biogeochemical and microbial processes may be altered by the fire. Changes to these below-ground 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 stabilise these processes following a fire.

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

VAR identification

To plan mitigation actions for post-fire effects, the BAER team first identifies and quantifies 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 and Ager 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 archaeological artefacts, 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.

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 the geographic information system (GIS) and the automated geospatial watershed assessment (AGWA) modelling tool. Fig. 3 illustrates the BARC product that was developed for the Elk Complex wildfire, which was based on Landsat imagery and was 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 to be 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 normalised burn ratio (dNBR) is used to detect changes between the pre-fire and post-fire infrared band values (Parsons *et al.* 2010).[4] Because burn severity cannot be expressed by a single quantitative measure, observed changes are grouped into classes (Lentile and Holden 2006), ranging from 'unburned' to 'high severity', and are integrated into the BARC map.

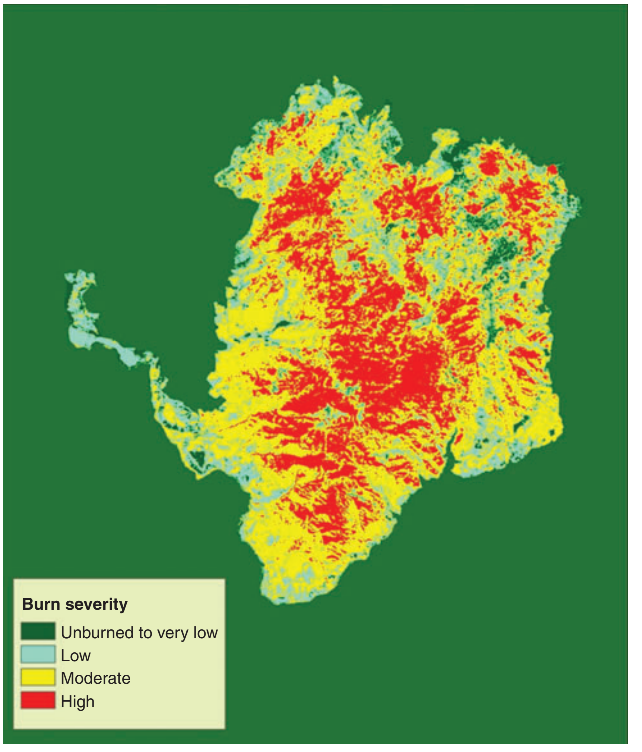

Fig. 3. BARC map of the Elk Fire portion of the Elk Complex Fire, which burned in the Boise National Forest, Idaho, in 2013. Source: USGS Earth Resources Observation and Science Center, via Justin Epting, USFS. Pers. comm. between Justin Epting, USFS GTAC and Richard Bernknopf, University of New Mexico, 9 May 2019. BARC, Burn Area Reflectance Classification; GTAC, Geospatial Technology and Applications Center; USFS, US Forestry Service; USGS, US Geological Service.

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.

At times, localised 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 the 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.

A BARC product is typically generated once for every incident where a BAER team submits a request. However, for

[4]Landsat data are input to the normalised burn ratio (NBR). 'The dNBR is a temporal difference between pre- and postfire to determine the extent and degree of change detected from burning.' (Key and Benson 2006; p. 1).

Table 1. Summary of soil burn severity classification factors
Source: Parsons *et al.* (2010), appendix E. MDI, mini-disc infiltrometer

Factor considered	Soil burn severity class		
	Low	Moderate	High
Aerial view of canopy	Tree canopy largely unaltered. Shrub canopy intact and patches of scorched leaves not dominant. Ash is spotty.	Tree canopy is scorched over 50% of area. Shrubs mostly charred but difficult to assess fuels from air. Black ash is visually dominant. Grey 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. Grey 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 <1 cm (0.5 inch) remain. Shrub density moderate or high.	90–100% charred canopy. Most branches consumed, including fuels <2.5 cm (1 inch). Skeletons or root crowns remain. Shrub density moderate or high. Often old growth in character.
Fine fuels (grassland)	Scorched or partially consumed.	Mostly consumed. Appear 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 mostly consumed.	0–20% cover remains as burned litter and woody debris under trees. Shrub litter is consumed.
Water repellence	Soils may be naturally water repellent under unburned chaparral. Other soils will infiltrate water drops in less than 10 s; greater than 8 mL min^{-1} with the MDI.	Surface of the mineral soil below the ash layer may be moderately water repellent but water will infiltrate within 10–40 s; 3–8 mL min^{-1} with the MDI.	Strongly water repellent soils (repels water drops for >40 s; 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 colour darkened or charred at surface or just below surface only.	Soil structure to 2.5 cm (1 inch) is degraded to powdery, single-grained or loose. Fine roots are charred. Pores are destroyed. Black charred soil colour common below thick ash layer. Compare with unburned.

long-duration incidents, multiple iterations of BARC products may be generated at the request of BAER teams.

SBS mapping

SBS is a classification that indicates the ecological effect 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 unfavourable properties and will require extra maintenance or costly alterations (Clifford 2013). Table 1 lists the 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, the BAER team members 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 modelling 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 BAER team geospatial specialist integrates the collected data 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.[5]

Case study: Elk Complex wildfire, Boise National Forest

In early August 2013, lightning strikes ignited two fires, the Elk and Pony, that blazed through the Boise National Forest in Idaho and swept into neighbouring mountain towns. Eventually, these fires merged and were referred to as the Elk Complex. By the time the fire was declared 100% contained on 31 August 2013, it had burned 52 998 ha in the Elk portion of the complex, which we focus on here. Nearly 75% of the burned area within the Elk portion of the complex 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).

[5]The automated geospatial watershed assessment model needs good observations of pre- and post-fire rainfall, runoff and erosion to be properly calibrated. Without high-quality observations, the resulting model estimates cannot be expected to closely predict actual runoff and erosion. Therefore, large relative changes between the pre- and post-fire modelled watershed responses are the primary metric to identify 'hot spots'.

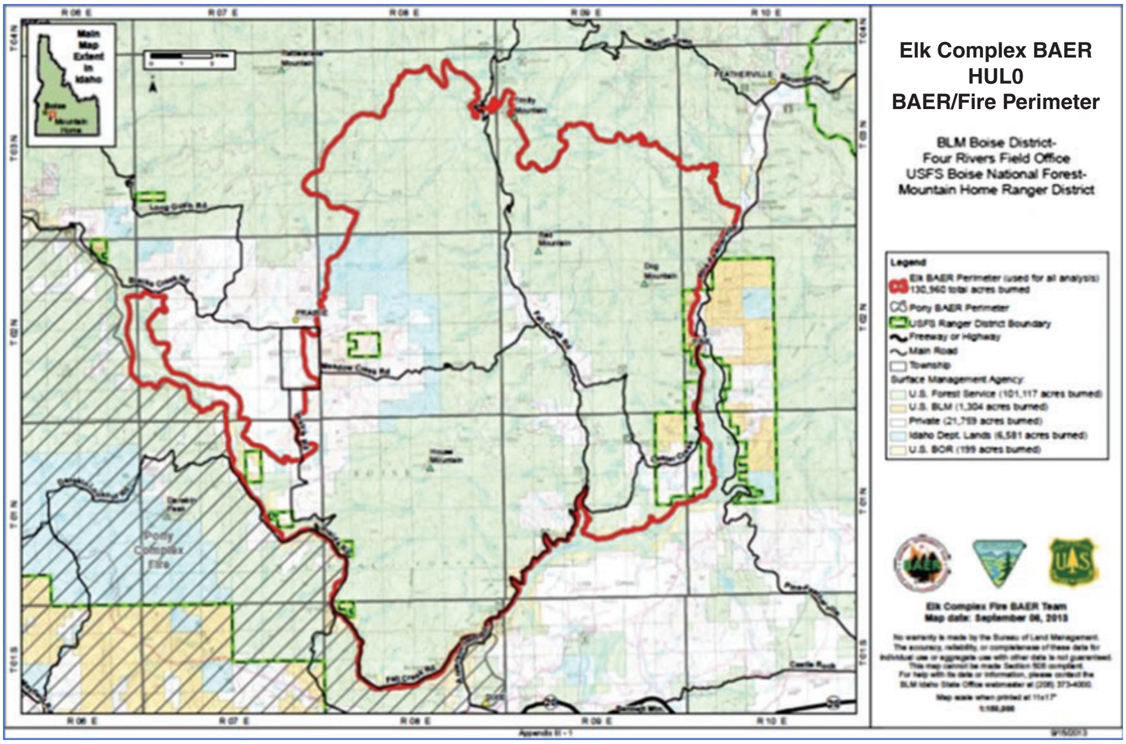

Fig. 4. Pre-fire map of the 2013 Elk component of the Elk Complex Fire in the Boise National Forest (Idaho).

BARC map production costs for reference case (R): Landsat imagery and helicopter response

The team designed and implemented an emergency stabilisation plan using core data derived from Landsat. GTAC obtained pre- and post-fire images from Landsat 7 on 17 August 2013 and created the BARC map (Clifford 2013). The final SBS map classified 13 470 ha as high burn severity, 25 504 ha as moderate burn severity and 10 864 ha as low burn severity. Using these classifications, the BAER team rated the VAR and prioritised the response actions. In the emergency stabilisation plan that was submitted on 9 September 2013, 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 ~6475 ha within the burned watersheds that had high burn severity and steep slopes. These hectares were considered treatable because they were unlikely to recover naturally and were located within a range of hillslope gradient that had been successfully treated after previous fires in the area. The BAER team also used the AGWA tool to simulate the watershed response for pre- 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 6475 ha originally considered treatable to between 809 and 1619 ha 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. Fig. 4 is a pre-fire map showing an outline of the area burned by the 2013 Elk component of the larger Elk Complex Fire. It shows pre-fire conditions for the Elk Complex Fire surface land agency ownership areas, cultural features, streams and BAER response perimeter boundary that were at risk of high SBS in the 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 to the satellite sensor are not substantial: 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 component of the fire (Fig. 5). The spatial patterns in the BARC map shown in Fig. 3 and the field verification were combined to determine the most accurate SBS classifications. BAER teams adjusted the BARC threshold values for the entire burned area through systematic editing.

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

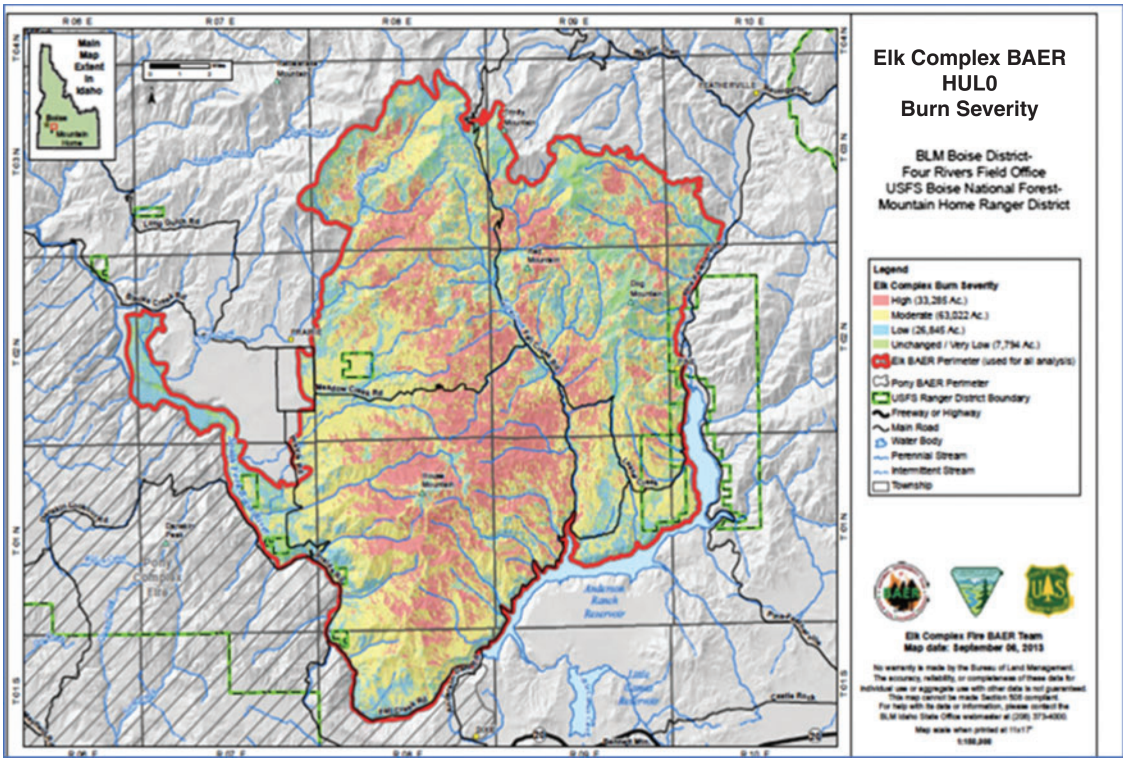

Fig. 5. Burn severity map of the 2013 Elk component of the Elk Complex Fire in the Boise National Forest (Idaho).

incurred in our reference case (i.e. when Landsat imagery was used). The major cost component is tied to an analyst's labour, 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 the BAER team can use a 'slider bar' approach to recalibrating 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 from the Multi-Resolution Land Characteristics (MRLC) consortium.

Table 2. BARC production cost per individual wildfire incident request

Source: Justin Epting and Brad Quayle. Pers. comm. between Justin Epting, USFS GTAC, Brad Quayle, USFS GTAC and Richard Bernknopf, University of New Mexico, 13 November 2018. All costs in USD. BARC, Burn Area Reflectance Classification; USFS GTAC, US Forestry Service Geospatial Technology and Applications Center

	(1) Landsat imagery	(2) Commercial imagery
Analyst labour[A]	\$365–480	\$365–480
Hardware[B]	\$2.93	\$2.93
Software[C]	\$75.57	\$75.57
Satellite imagery	\$0	\$500–1000
Total cost for individual BARC request	\$443.50–558.50	\$943.50–1558.50

[A]Estimated to be 7–8 h 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).
[B]Assumes 150 BARC requests received by the USFS over a year (\$440 per 150 requests).
[C]Annual USFS cost of \$113 35 for software licenses for ERDAS Imagine and ESRI ArcGIS scenes.

BARC map production costs for counterfactual cases: (A) commercial imagery and helicopter response; (B) helicopter response only

Our counterfactual cases assumed that Landsat imagery was not available and that the BAER teams found ways to create BARC and SBS maps comparable to those produced when Landsat imagery was available.

The first counterfactual case was commercial purchase of a single Landsat scene-equivalent (for production costs associated with this case, see Table 2, Column 2). Costs were similar to those for when Landsat imagery was available (Table 2, Column 1), except for a fee-per-scene of US\$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 involved only helicopters and was performed exclusively by the BAER team. Video footage was collected, processed and georeferenced to map SBS. In this case, the fire was divided into zones – the team locates itself at high points and draws on maps with coloured pencils. This process requires someone to digitise the drawings by hand for suitable input to GIS, a task that can be time consuming when on deadline for creating an SBS map.

BAER costs

A BAER assessment has different costs depending on whether a BARC map is available for support following a wildfire incident. Fire attributes 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-m 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 have an effect on 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, we developed estimates of the BAER assessment costs for the reference and counterfactual cases. 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 h × 2 days. The unit cost for a task also varies by fire size based on the following breakouts: 0–12 141 ha, 12 141–80 937 ha, and >80 937 ha). For the Elk Complex Fire, the personnel cost is based on a fire size of 52 998 ha. We assumed that a task was accomplished by an employee at the GS-11 level of the federal government pay scale at a cost of US$60.16 per hour for 2088 h in a year. This cost includes salary, benefits (35% of salary), and facilities and administrative costs (52% of salary).

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 require less GIS

Table 3. BAER protocols and process costs for the Elk Complex Fire

Source: T. J. Clifford. Pers. comm. between T. J. Clifford, Bureau of Land Management and Richard Bernknopf, University of New Mexico, 1 October 2018. All costs in USD. BAER, Burn Area Emergency Response; BARC, Burn Area Reflectance Classification; GIS, geographic information system; SBS, soil burn severity

			Reference case (R)			Counterfactual case (A)			Counterfactual case (B)		
			Landsat imagery and helicopter response[A]			Commercial imagery and helicopter response			Helicopter response only		
General task	Resource	Units	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	$6738	168	$60.16	$10107	448	$60.16	$26952
Helicopter mapping	Persons	Hours	16	$60.16	$963	32	$60.16	$1925	64	$60.16	$3850
Helicopter video and photo processing	Persons	Hours	8	$60.16	$481	32	$60.16	$1925	24	$60.16	$1444
GIS processing from field/helicopter to final SBS	Persons	Hours	8	$60.16	$481	16	$60.16	$963	72	$60.16	$4332
GIS processing from BARC to final SBS	Persons	Hours	8	$60.16	$481	6	$60.16	$361	0		$-
Helicopter use (pilot, fuel-truck driver)	Persons	Hours	4	$300	$1200	8	$300	$2400	16	$300	$4800
Helicopter fuel	Fuel	Hours of fuel	4	$500	$2000	8	$500	$4000	16	$500	$8000
Helicopter contractual use (cost)	Availability	Days	0.5	$3000	$1500	1	$3000	$3000	2	$3000	$6000
Total			**171.5**	**$4400**	**$14505**	**279**	**$4400**	**$25162**	**660**	**$4350**	**$66481**

[A]Helicopter response involves costs associated with a pilot, fuel, fuel-truck driver and mechanic. A helicopter day = 14 h.

Table 4. Estimated total incident cost and savings for the Elk Complex Fire
All costs in USD. BAER, Burn Area Emergency Response; BARC, Burn Area Reflectance Classification

	Reference case (R) Landsat imagery and helicopter response[A]	Counterfactual case (A) Commercial imagery and helicopter response	Counterfactual case (B) Helicopter response only
BARC map production	\$443.50–558.50	\$943.50–1558.50	N/A
BAER protocol and process	\$14 505.00	\$25 162.00	\$66 481.00
Total	\$14 948.50–\$15 063.50	\$26 105.50–\$26 720.50	\$66 481.00
	Cost comparison of reference and counterfactual alternatives		
Savings (B – R)		\$51 418.00–51 532.50	
Savings (B – A)		\$39 760.50–40 375.50	
Savings (A – R)		\$11 157.00–11 657.00	

[A]Helicopter response involves costs associated with a pilot, fuel, fuel-truck driver and mechanic. A helicopter day = 14 h.

processing than previously needed for 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 the 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 the 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 utilised for satellite imagery.

Difference in total costs: reference and counterfactual cases

Savings per incident

Savings realised under the BAER protocol when Landsat imagery was available for the reference case, relative to scenarios in which Landsat imagery was not available for the counterfactual cases, are given by the differences in the totals in the last row of Table 3. The total savings, which included costs for both BARC map production and the BAER protocol, are shown in Table 4. The reference case was associated with per-incident savings that ranged between US\$11 157 (using commercial satellite imagery and helicopter response) and US\$51 418 (using helicopter response only).

Multi-year cost savings

In busy years, GTAC may receive 125–150 USFS BARC requests from BAER teams. Based on the cost savings per incident (see Table 4), we estimated the savings of using Landsat imagery for BARC map production and BAER response over a 5-year period. The effectiveness measure for analysis was the number of incident requests per year, which we assumed as 150 incident requests per year for BARC products. It was assumed that all wildfires were of the same size and complexity as the Elk Complex Fire. In addition, although we assumed that the average fire incident was constant for the 150 incidents per year, input costs associated with fieldwork and other tasks for each incident can vary as fire size increases and terrain becomes more challenging. Based on GTAC historical data, we assumed that two scenes were acquired for a BARC request (pre- and post-fire). Furthermore, there were 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 assumed that the hardware cost was a one-time investment in the initial year of the program C_0 and that operating costs C_t were incurred during years 1–5. The GTAC cost-effectiveness CE was estimated by applying the formula in Eqn 1:

$$CE = C_0 + \sum_{t=1}^{T} \left[C_t \cdot (1+r)^{-t} \right] \qquad (1)$$

where C_0 is investment cost, C_t is operating cost, t is time in years and r is the discount rate.

For counterfactual case A (commercial imagery and helicopter response), assuming an initial investment cost in a computer of US\$2200, the operating cost savings per year for 150 incident requests ranged from US\$1.7 million to US\$1.8 million, depending on whether the low or high cost estimates were used for Landsat and commercial satellite imagery. The present value of the cost savings from using commercial imagery instead of Landsat imagery for the 5-year investment period ranged between US\$7.5 million and US\$8 million, assuming a 3.5% social discount rate.

For counterfactual case B (helicopter response only), the operating cost savings per year for 150 incident requests was US\$7.7 million. Thus, the present value of the cost savings from using Landsat imagery instead of a helicopter-only response for the 5-year investment period amounted to approximately US\$35 million (again assuming a 3.5% social discount rate).

Conclusion

In this study, we demonstrated that BARC is a cost-effective input to wildfire management and post-fire mitigation assessments. We documented the costs for a reference case in which the production of a BARC map and its use in the BAER protocol took place when Landsat imagery was available. We compared the costs in our reference case to costs incurred in counterfactual cases (in which Landsat imagery was not available). The counterfactual cases relied on data from a combination of commercial satellite imagery and helicopter response or on a 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 was the most cost-effective alternative.

Although this study demonstrated the savings of using Earth observations in post-wildfire response, it identified but did not quantify the potential benefits of using satellites 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 savings we quantified 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.

Conflicts of Interest

The authors declare no conflicts of interest.

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