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A method for estimating the socioeconomic impact of Earth observations in wildland fire suppression decisions

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Abstract. A method for estimating the socioeconomic impact of Earth observations is proposed and deployed. The core of the method is the analysis of outcomes of hypothetical fire suppression scenarios generated using a coupled atmosphere–fire behaviour model, based on decisions made by an experienced wildfire incident management team with and without the benefits of MODIS (Moderate Resolution Imaging Spectroradiometer) satellite observations and the WRF-SFIRE wildfire behaviour simulation system. The scenarios were based on New Mexico's 2011 Las Conchas fire. For each scenario, fire break line location decisions served as inputs to the model, generating fire progression outcomes. Fire model output was integrated with a property database containing thousands of coordinates and property values and other asset values to estimate the total losses associated with each scenario. An attempt to estimate the socioeconomic impact of satellite and modelling data used during the decision-making process was made. We analysed the impact of Earth observations and include considerations for estimating other socioeconomic impacts.

Additional keywords: fire economics, fire management modelling, fire simulation modelling, remote sensing, socioeconomic analysis.

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Introduction

Satellite observations have often been used for fuel type mapping, fuel moisture content mapping, long-term fire risk modelling, fire detection and fire severity mapping. Although progress has been made in each of these areas, much work still remains before we have an effective integration of satellite observations with local fire behaviour models that enhance decision support tools at the operational level (Chuvieco and Kasischke 2007); see also Hassan and Petropoulos (2018), whose special issue 'Remote sensing of wildfire' contains not a single article on this type of integration, and Dunn *et al.* (2017), who emphasise the paucity of research addressing the use of information tools for managing risk when responding to wildfires. To that end, the present paper discusses how such fire suppression decision-tool enhancements can be developed to help address one 'of the largest knowledge gaps: modelling relationships between fire management activities and avoided damages' (Thompson *et al.* 2017, p. 562).

The Values at Risk (VAR) concept, including human life, can be formally incorporated when modelling and making wildland fire decisions during an incident (Thompson *et al.* 2017). However, the VAR notion remains inherently broad and vague, especially when confronting a new fire. In addition, the dollar values of all assets at risk are often not available to the incident management team (IMT). Federal estimates have focused on easily measured impacts, i.e. suppression costs, area burned and structures destroyed (Thomas *et al.* 2017). Long-term and broader impacts are not tracked: environmental damages and forest treatment costs, societal and local health impacts, plus other direct and indirect economic effects. The fact that direct fire suppression costs are only a fraction of the total socioeconomic impacts of wildfire (e.g. Dale 2010) spotlights the lack of a standard methodology for measuring the long-term and indirect costs of wildfire.

For practical implementation of the VAR concept in a complex fire, each category of highly valued resources and assets (HVRAs) should be assigned values by the best method for that category (Scott *et al.* 2013). That is, the losses or benefits within a category are totalled, and then combined with other HVRA categories' results to calculate the fire's total impact. Scott *et al.* (2013) and Calkin *et al.* (2010), who wrote the initial US Forest Service (USFS) report proposing the HVRAs method, appear to agree on the three major characteristics describing HVRAs – spatial maps, response functions and relative importance. The ranking of relative importance assigns relative values to disparate resources and assets. However, the ranked values vary according to evaluator opinions, and may omit community values (Williams *et al.* 2018).

Table 1. Classification of resource and asset values

A proposed loss classification template (including cause of loss) for wildfire effects in general, tailored here for the specifics of Las Conchas, the focus of this study. NA, not applicable – by definition or convention, this type of value is not monetised; x, for this study, such a value is treated as either monetary or non-monetary; ?, without detailed data, the value cannot be monetised – though monetised, the value may have non-monetised value that is not reflected here

Type	Monetised	Non-monetised	Fire or flood
Human			
Life and safety	NA	x	Both
Evacuation	?	x	Fire
Social and cultural			
Archaeological (Bandelier)	NA	x	Both
Lost time or productivity	?	x	Fire
Natural landscape (Pueblos)	NA	x	Both
LANL	NA	x	Fire
Property and revenue			
Size of fire	NA	x	Fire
Private property losses	x	?	Both
Timber	x	?	Fire
Bandelier National Monument	x	?	Both
Los Alamos National Laboratory	x	?	Fire
Pueblos	x	?	Both
Ecological			
Timber	NA	x	Fire
Flora and fauna	NA	x	Both
Watershed(s)	NA	x	Both

HVRA is less comprehensive than socioeconomic impact analysis (SEIA); see NASA (2012) for an accepted SEIA methodology, and Rijal *et al.* (2018) for a cost–benefit analysis of fire management and timber. Although an SEIA may stress monetised values more than HVRAs, it has a long history of estimating both monetary and non-monetary values (Bureau of Rural Sciences 2005).

IMTs use a variety of information including satellite data, maps, fire spread models, geographical information systems (GIS) and management plans, but there are no set protocols on how to add HVRAs to their decision-making process, especially considering the numerous types of HVRAs that an IMT encounters on assignments, which are highly variable in terms of fire complexity, fuel types and risks.

The complexity of assigning HVRA values can be seen in the recent work of Thompson and colleagues. In a wildfire study estimating the modelled HVRAs burned in geographic polygons representing specific types of HVRA (municipal watersheds and a critical wildlife species), Thompson *et al.* (2013) included these HVRAs with their attached geospatial coordinates when projecting fire perimeters and wildfire impacts for the two case studies. Similarly, Thompson *et al.* (2016*a*) relied on Los Alamos County cadastral maps to provide values for the building clusters and acreage threatened in their study of the Las Conchas fire. This analysis recognised two types of HVRA–urban clusters and Los Alamos National Laboratory (LANL) acreage. The same complexities are inherent to an SEIA.

A comprehensive HVRA or SEIA implementation remains in the future. The purpose of the present work is not a complete impact analysis of the 2011 Las Conchas fire. Our experiment was designed to address two specific questions in the same setting: how do Earth observations and fire progression model outputs affect wildland fire suppression decisions, and what is the socioeconomic impact of providing this information to the wildfire IMT? Based on our literature searches, neither of these questions has been formally explored, though there are recent examples of using satellite data and simulations to enhance situational awareness (e.g. Jolly and Freeborn 2017; Jiménez *et al.* 2018).

Valuation of losses

Our research method starts by specifying the dollar values and geographic locations of multiple HVRAs such as homes and timber, into the 2011 Las Conchas fire area with a progressing fire perimeter generated by WRF-SFIRE (WRF, Weather Research Forecasting), which provides burn times for each location and allows us to calculate the total value impacted for each simulated scenario. Utilising these values helps to build a picture of the impact caused by fire suppression decisions made in a series of scenarios. In addition, the SEIA allows us to distinguish between monetised, human, social and ecological values.

In our review of the literature, HVRAs appears to focus on the value of property and timber. Ideally, HVRAs would assign relative importance values to all assets and resources including important human, social and ecological values also threatened by wildfire. By adding property and revenue values to these three broad categories, we would have an SEIA categorisation scheme similar to the triple-bottom line concept of Elkington (1994) and Savitz and Weber (2006), which underlies sustainability reporting now practised by 85% of the Standard & Poor's 500 companies (G&A 2018). Given the importance of sustainability to ecologists and the prioritisation of human life within the wildland fire community, these four categories seem most relevant for wildfire purposes and overlap with the suppression objectives espoused by Dunn *et al.* (2017). The unique value of human life is widely accepted across the wildfire community (Harbour 2018; in the Standard Firefighting Orders, safety is the tenth and final one), and although one can actuarially monetise the value of a human life, to date that has not been the accepted practice in wildfire decision-making. The challenge of monetising social or ecological values is well expressed by the Santa Clara Pueblo Governor (Dasheno 2011) in testimony to the US Senate:

> 'Some costs are impossible to calculate, such as:
> What is the value of a forest?
> What is the worth of a canyon?
> How do you apply numbers to a sacred site?
> How do you calculate the meaning of pure water used for traditional purposes?
> What if an event is so great in magnitude that it even affects the identity of one's people?
> While these questions cannot readily be answered, we are putting pen to paper…'

Considering these difficulties, our SEIA distinguishes between monetised and non-monetised resources and assets in those cases where such a distinction seems reasonable and warranted. In addition, we recognise that some assets, e.g. Bandelier National Monument, could be categorised as both property and social. Table 1 shows the impact on specific Las Conchas assets and

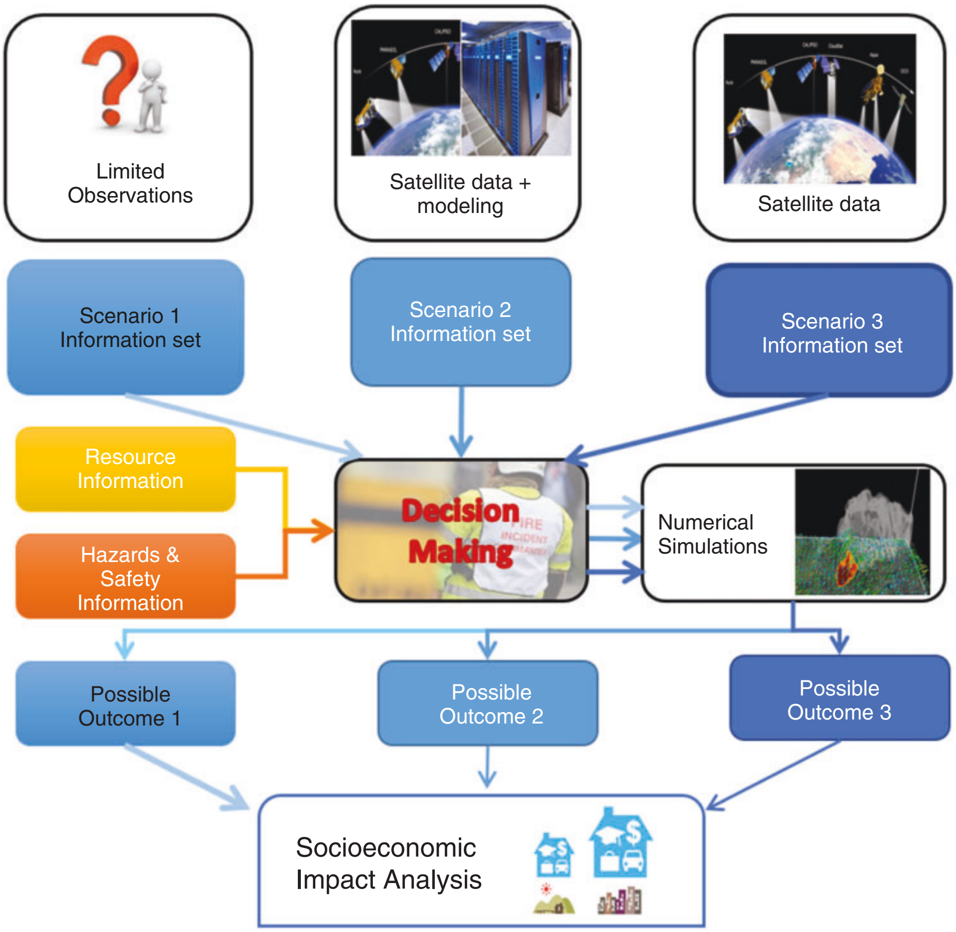

Fig. 1. The scenarios and modelling information flow diagram shows which information was made available to the incident management team under each simulated scenario.

resources, their valuation type and the cause of loss to those values. The Supplementary material contains a more detailed description of the specific assets and resources threatened or impacted by the Las Conchas fire.

Exercise design

To analyse the 2-day operational exercise for wildfire decision making with and without utilising infrared satellite images, our plan was to run the WRF-SFIRE model for each scenario and then estimate the socioeconomic impact of each scenario's different suppression activities (Fig. 1). This plan assumed that the Earth images from MODIS (Moderate-Resolution Imaging Spectroradiometer) would provide information to the IMT that could cause them to modify their suppression activities. The role of the numerical simulations was to construct the hypothetical fire progression scenarios based on the IMT suppression decisions.

Simulation period

The Las Conchas fire burned for more than 1 month. The longer the wildfire simulation, the further a model will diverge from the actual historical fire outcome. To reduce modelling uncertainty, we limited the scope of our simulation to a 2-day experimental time window from 0800 hours on 29 June 2011 to 0800 hours on 1 July 2011 (all times are local). We selected this time period for the following reasons:

- Two-day fire simulations more closely track a historical fire's progression than simulations of longer forecasting periods.
- The first 2 days of the Las Conchas fire were ruled out owing to severe weather and no formal IMT being in place. High winds made direct engagement with the fire on 26–27 June 2011 unsafe or impossible on much of its perimeter, offering few alternatives for decision making and model testing.
- Reliable information became available only after a national IMT took charge of the wildfire on 28 June. A good fire perimeter map was also issued at 2343 hours on that date (Fig. 2), and with the arrival of the IMT, Incident Action Plans (IAPs) and Incident Status SummaryICS209 forms, the crew and equipment assignments became documented. Thus, 29 June seemed the ideal date for starting the experiment.

See Supplementary material SD for a more detailed description of the progression of the fire.

Simulation software

The simulations were performed using WRF-SFIRE (Mandel *et al.* 2009, 2011, 2014; Kochanski *et al.* 2016), which uses

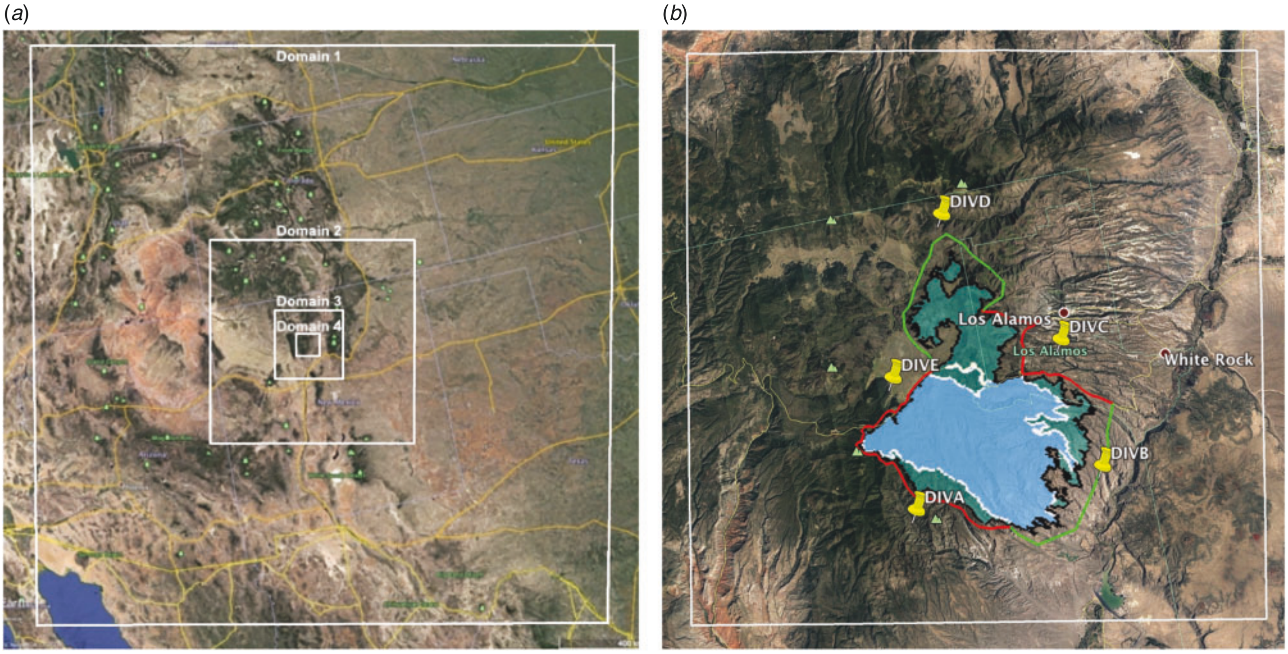

Fig. 2. Map (*a*) sets up the hierarchy of WRF-SFIRE domains. Map (*b*) shows the highest-resolution Domain 4 with the fire perimeter at 27 June 2011 0309 hours local time (LT) (blue with white outline) and at 28 June 2011 2343 hours LT (green with black outline) provided to the incident management team (IMT) consultants as a part of the baseline Scenario 1. Red lines represent fuel break lines (active fire suppression); green lines represent monitoring lines (observation only).

Rothermel's (1972) parameterisation of the rate of spread, with the fire spread implemented by the level set method, coupled with the WRF model (Skamarock *et al.* 2008). WRF-SFIRE evolved from the Coupled Atmosphere-Wildland Fire Environment modelling system, CAWFE (Clark *et al.* 2004), which coupled fire spread implemented by tracers with the Clark–Hall atmospheric model. WRF-SFIRE has been a part of WRF since release 3.2 as WRF-Fire (Mandel *et al.* 2011; Coen *et al.* 2013), which was recently selected as a foundation of the operational Colorado Fire Prediction System (Jiménez *et al.* 2018), and the level set method was improved (Muñoz-Esparza *et al.* 2018). WRF-SFIRE is open-source software, available at https://github.com/openwfm/wrf-fire (accessed 22 July 2019).

Model setup

The model was set up with four nested domains with horizontal resolutions gradually increasing from 12 km to 444 m (Fig. 2). The first vertical model layer was placed 5 m above the ground. The fire component was executed in the innermost domain with resolution mesh 22 m (1 : 20 refinement ratio with respect to the atmospheric mesh). All simulations were started on 29 June at 1100 hours local time (1700 UTC, Coordinated Universal Time). Atmospheric initial and boundary conditions were generated from Climate Forecast System Reanalysis (Saha *et al.* 2010) provided at 6-hourly intervals at the horizontal resolution of 36 km. The presented method was executed in the hindcast mode: as the simulation period was in the past, we opted for using atmospheric reanalysis data, rather than the forecast data, to exclude the impact of the weather forecast error on the calculated socioeconomic impact. More details on the modelling setup are presented in Supplementary material SF, and Table S1 therein.

Satellite data

Active fire detections from satellite sensors recently have become an important source of information for wildland fires. Polar-orbiting satellites Aqua and Terra with the MODIS sensors fly over the same location anywhere on the Earth twice a day each at approximately the same time, providing images with 1-km resolution at nadir. The multiband infrared images are then processed into fire detection products in near-real time and posted on the internet (Giglio *et al.* 2003, 2016). For the purpose of this exercise, we had planned to utilise the product commonly used in the field, namely Active Fires detection available from the USDA Forest Service Active Fire Mapping Program (https://fsapps.nwcg.gov/afm/, accessed 22 July 2019) rather than science-level data. This product is released daily for the continental United States and it consists of pixels of nominal 1-km size in arbitrary locations, with the colour scale indicating the age of the detection, from bright red for current detections to dark yellow for 1 week old. The product is delivered as KML files and viewed in the *Google Earth* software, which integrates the detection with 3D terrain and allows easy zooming in on the area of interest. The fire radiative power (FRP) product consists of pixels in the same location, coloured by the FRP. Detection may not be possible for reasons including clouds, and unlike the more complicated science-level products, there is no distinction made between no fire and no data. The more advanced Visible Infrared Imaging Radiometer Suite (VIIRS) sensor, now in common use, was launched on the Suomi NPP satellite later in 2011, so there are no VIIRS data for the fire studied.

We had expected to show the commanders the standard MODIS Active Fires product described above, but, unfortunately, the website had been just moved from previous FireMapper.gov, and historical KML files were (and still are) either missing or did

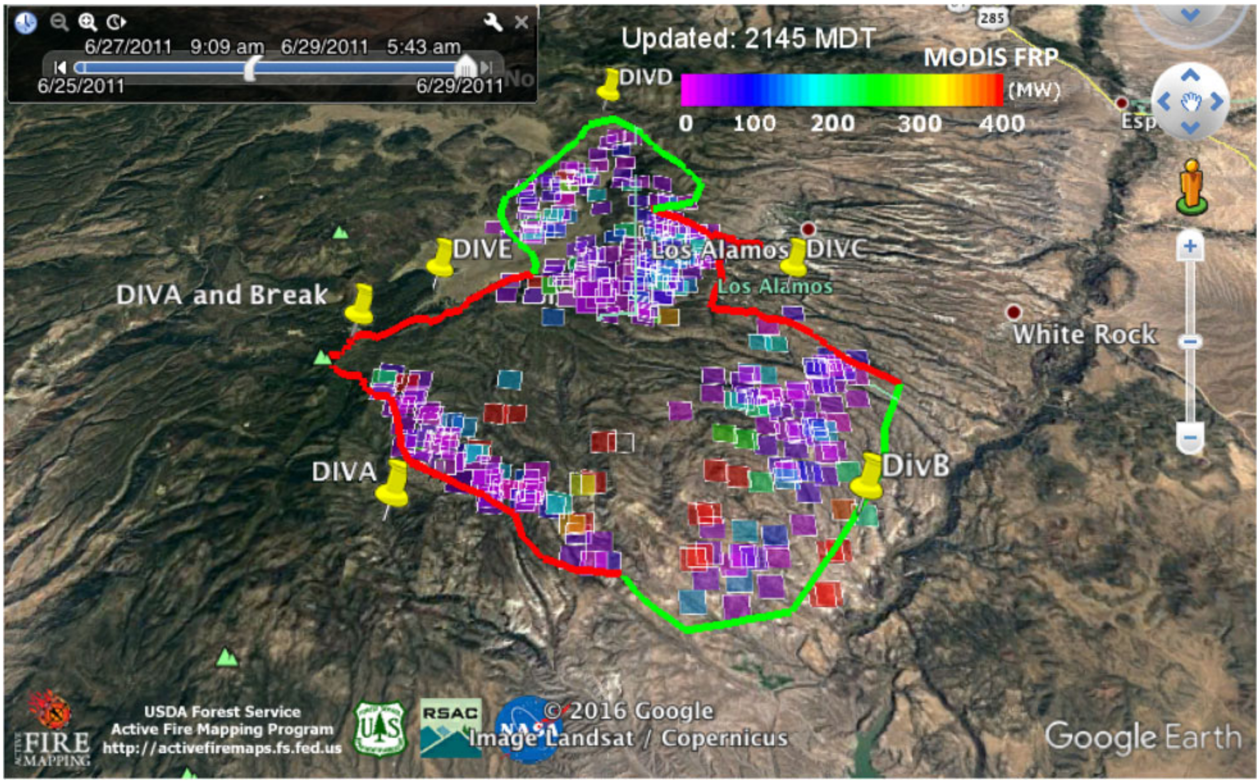

Fig. 3. Scenario 1 fireline divisions drawn by the incident management team (IMT) consultants overlaid on image of MODIS fire detections to date, selected by the time slider. Red lines are active fire suppression. Green lines are observation only. UTC equals Local Time (LT) minus 6 h. Note MODIS hotspots located north of the Division line C. MDT, Mountain Daylight Time (local time); FRP, Fire Radiative Power.

not function properly, as they need online components that no longer exist. Fortunately, the same fire detection data were still available in the comma-separated values (CSV) format and we quickly wrote software to produce our own KML files, which is available at https://github.com/openwfm/wrfxpy/blob/master/csv2 kmz.sh (accessed 22 July 2019). The CSV files have one detection per line, including the longitude and latitude (in WGS84 datum) of the detection pixel, the confidence level and the FRP. As in the original FireMapper's KML files, the fire detection pixels in our KML files are painted as square pixels of nominal side length 1 km, in arbitrary locations. However, whereas the FireMapper KML files use colour for ageing the detection pixels, we have chosen the FRP power colour scale, and encoded the time by the time tag in the KML file, which allowed us to use the *Google Earth* time slider to select fire detections in a specific time interval (Fig. 3) or to display the time progression of all detections as an animation.

Calculating losses

To calculate asset value losses, the model simulations provided an estimate of the fire progression as the fire arrival time generated by WRF-SFIRE. We assembled a database as a spreadsheet (CSV file) with assets' longitude, latitude and values. Each asset was assigned the time of burning by interpolating the fire arrival time to the asset location from the fire model grid. Assets with fire arrival time within the specified simulation time window were considered lost, and their values were added.

To estimate the value of the timber lost, each model cell at 30-m resolution was assigned a value according to the fuel type in the cell on the model grid. The timber in cells having fire arrival time within the specified simulation time window was considered lost, and the values of these cells were added.

Property values were estimated from county data. Our search found no local timber harvest market price per acre data and no local harvest volume data for any years before and after the Las Conchas fire. Instead, timber values were estimated from harvest values, based on tables used for California tax valuation of timber producing property (CA Board of Equalization 2011). See Supplementary material SA and SB for the data collection methodology, the assumptions used and further details.

The assigned asset values only approximate 2011 northern New Mexico market values. The nominal values used in our scenarios are illustrative only. They are intended to serve in comparing hypothetical simulated scenarios. We simulated estimated partial damages incurred during only 2 days of a fire that was not fully contained for 24 days. We made no attempt to quantify the actual damages caused by the historical fire in total or for any individual or category.

Scenarios

The scenarios in our experiment were defined by which types of information were provided to the assembled IMT. After considering the provided data, the IMT made fire suppression decisions, which were used as an input to the fire progression model. The

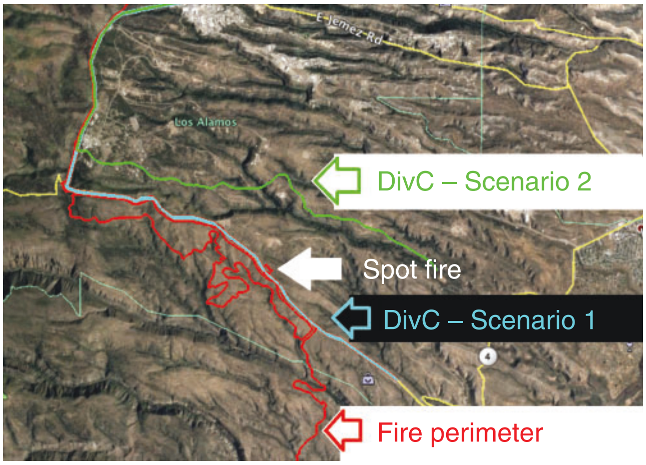

Fig. 4. Division C fire break line change from Scenario 1 (light blue line) to Scenario 2 (green line). Red line is the fire perimeter at the beginning of the scenarios. The white arrow marks a spot fire located north-east of Highway 4.

IMT was provided by consultants from Wildland Fire Associates (WFA), namely this paper's coauthors Rich McCrea and Dan O'Brien, each with decades of wildfire management experience. We understand the importance of the IMT in suppressing a wildfire and recognise the fact that our team consists of only two individuals in a single setting. With this caveat, we note that actual IMTs are not infallible, cf. Katuwal *et al.* (2017) and Hand *et al.* (2017) for findings critical of IMT performance, which highlight the need for additional research into fire suppression decisions. What follows next is a discussion of the experiment.

Scenario 1 – base case

Scenario 1 represented the experiment's baseline and was the first of three scenarios that the WFA consultants would undertake. In this first scenario, the intent was to introduce the WFA consultants to the overall purpose of our study and to the available documentation, i.e. maps, IAPs, ICS209s and Wildland Fire Decision Support System (WFDSS) reports. The documentation included the weather forecast for 29 June 2011, the availability of firefighting resources and the fire's perimeters on 27 June 2011, 0309 hours and on 28 June 2011, 2343 hours local time (Fig. 2*b*).

This first decision for suppression actions on 29 June 2011 provided the input for WRF-SFIRE to model Las Conchas fire's progression for the 2-day simulation. The WFA consultants drew firelines in *Google Earth* with a fire perimeter overlay, assigning five fireline divisions (Fig. 2*b*), labelled A through E. Division D outlined the north end of the fire from the Pajarito Ski Area to the west side of the fire at NM Highway 4 near the Jemez River. Winds were predicted to push fire to the north and create a major risk to any personnel in these rough canyons loaded with heavy fuels. For safety reasons, the IMT decided not to staff this division and to monitor it by air. Division E separated the fire from Valles Caldera to the west. This line ran along NM Highway 4 south-west from the end of Division D to the Division A anchor point. Fuels were mostly grass. Using the existing road for a fire break, the IMT decided to fully staff this division with engines to patrol, mop up and eliminate spot fires.

A small spot fire on LANL land just east of Highway 4 can be seen in the 28 June 2011 fire perimeter map (Fig. 4). In the real fire, this spot fire was quickly extinguished on 27 June 2011 (Rushe 2011), but in our base-case simulation for Scenario 1, the Las Conchas fire spread uncontrolled through LANL and into the town of Los Alamos. This unexpected outcome was due to the IMT's placement of the fireline for Division C in *Google Earth*. The original fire break line was drawn using *Google Earth* based on the infrared perimeter from 28 June 2345 hours that did not include the spot fire. This positioned the Scenario 1 Division C fire line along NM Highway 4 and did not encompass the spot fires on the east side of the road. For that reason, the numerical simulations generated fire expanding from these points, beyond the chosen fire break lines through most of LANL during the first 24 h of Scenario 1.

Scenario 2

In the fire simulation for Scenario 2, the fire break line has been moved approximately 6 km northward of the original Division C to encompass the spot fires evident in MODIS detections. This modification was implemented to ensure that the fuel break line encompassed all the fire activity north from NM Highway 4, making it effective in terms of blocking the northward fire propagation.

Scenario 3

For Scenario 3, the IMT had all the information provided in the first two scenarios plus additional infrared satellite images (MODIS) of the Las Conchas fire south-west perimeter from late evening 28 June 2011 into early morning 29 June 2011 (Fig. 5). They were shown a video of combined infrared images relevant to Division A operations that depicted hotspots moving to the south-west. The IMT made changes related to firefighter safety, described in the *Results* section, which, however, did not impact the fire propagation within the simulation window, so no new simulation was done. After this, the IMT was shown simulated fire behaviour provided by WRF-SFIRE. In this scenario, as in those earlier, the fire did move aggressively north towards the Santa Clara watershed. However, the IMT made no further changes to their suppression decisions because LANL and Los Alamos continued to be protected and spared direct fire damage.

We had originally planned this scenario to be the first in which MODIS data were provided to the firefighting decision makers, and another scenario in which WRF-SFIRE output was provided. The intention was to isolate and separately calculate the socioeconomic impact of MODIS data and WRF-SFIRE modelling output. However, we were unable to separately estimate MODIS data and WRF-SFIRE modelling output impacts because some data from both sources were already used together in Scenario 2.

Error considerations

Fire suppression

Owing to the insufficient data in the documentation describing the firefighting activities, the actual reconstruction of the fire was not attempted. The documentation we obtained under the Freedom of Information Act (FOIA) consisted of IAPs, which specify the resources, such as crews and equipment, and a verbal

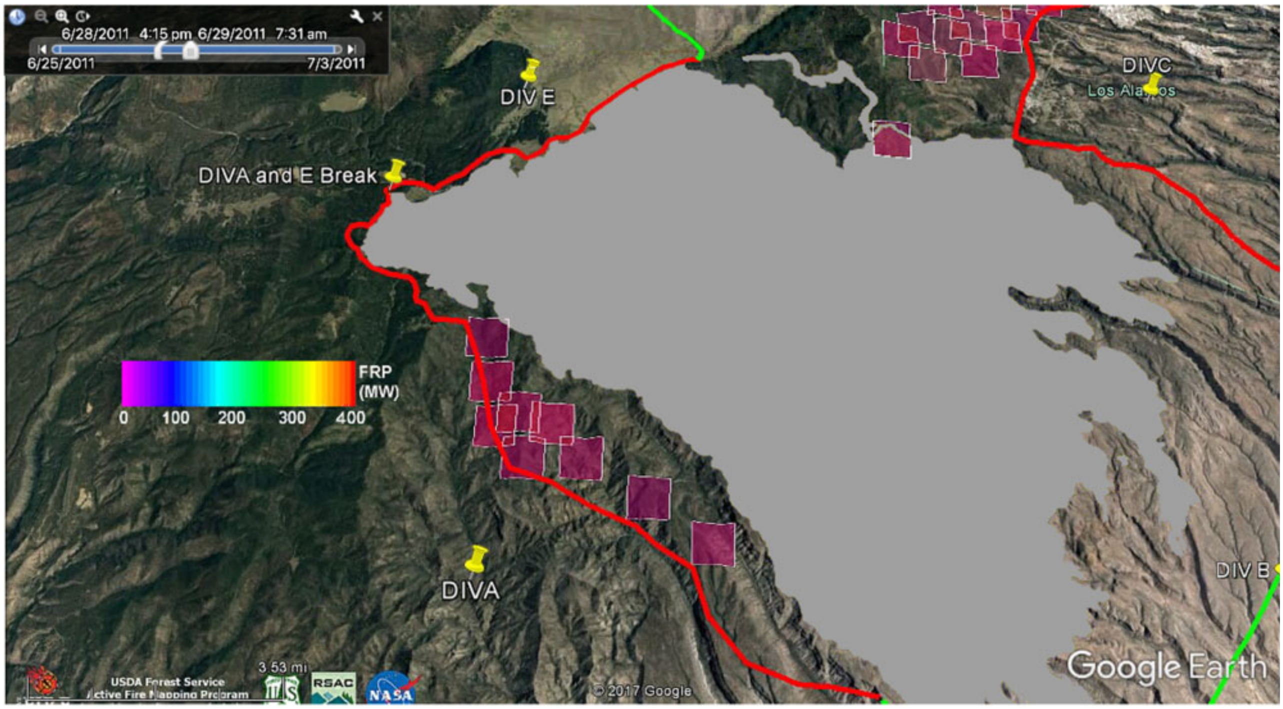

Fig. 5. Overnight fire detections (coloured squares) data from MODIS were provided for Scenario 3, showing greater fire intensity along Division A than was anticipated by the incident management team (IMT) in simulated Scenarios 1 and 2. Colour scale legend refers to MODIS detections only. Bold red lines are Division A, C and E firelines. Bold green lines are Division B and D observation lines. Grey is the burned area at the time indicated on the slider (upper left). FRP, Fire Radiative Power.

description of the general areas assigned, but no coordinates and no description of what was done. Owing to the lack of the exact locations and the extents of fuel break lines, as well as their start and finish times, implementing the effects of fire suppression was not possible. Our IMT explained that the Operations Section does not report 'completed fuel breaks or fire lines' until those areas are fully secure and they can be assured the fire will not escape those barriers. This is understandable, but it confounds efforts to conduct a fire behaviour analysis during or after the fire. There is no required documentation for when a fire break is constructed, other than information Operations maintains within their own section. The same is true for burnout operations, which are often not reported until after the fact. Therefore, the numerical simulations used in this study should not be treated as a reconstruction of the historical fire progression. Their main role was to generate hypothetical fire progression scenarios in response to fire suppression decisions based on similar resources. As the scenarios analysed in this study are artificial, they cannot be used for the model validation. The economic analysis presented here is intended to highlight the value of the Earth observations, rather than to calculate the actual cost of the Las Conchas fire.

The computational model

WRF-SFIRE was validated based on the experimental data collected during the FireFlux experiment (Kochanski *et al.* 2013*a*) as well as on selected wildfire cases (Kochanski *et al.* 2013*b*; Mandel *et al.* 2014). Sensitivity of WRF-SFIRE to parameters for smoke plume measurements was explored by Kochanski *et al.* (2018). As the error in fire spread grows over time, the model was periodically restarted from daily fire perimeters with infrared mapping, using spin-up to keep the atmosphere and fire states consistent (Mandel *et al.* 2014).

MODIS fire detection

The MODIS active fires detection algorithm was validated by a statistical analysis using other, fine-resolution instruments to detect the burning subpixels of MODIS pixel, and a statistical logistical regression model (Schroeder *et al.* 2008). The nominal resolution of MODIS data is 1 km; however, the pixels may be larger depending on the scan angle.

Valuation

Property tax valuation standards and practices vary by region. Property values for tax purposes obtained from the counties were used as a proxy for market values with no attempt at market value adjustment. New Mexico law does specify a uniform procedure intended to reflect market values across counties. Determining market value variations is outside the scope of this study. We used these values only to compare the scenarios with each other.

Our timber valuations should be considered nominal. Our intention here also was to produce reasonable values for comparison between scenarios, not for comparison with historical market conditions or with timber market effects from the fire itself.

Results

Losses of property and timber

The difference of the areas consumed by fire in the simulations of Scenario 1 and 2 involved most of LANL (Fig. 6). Table 2

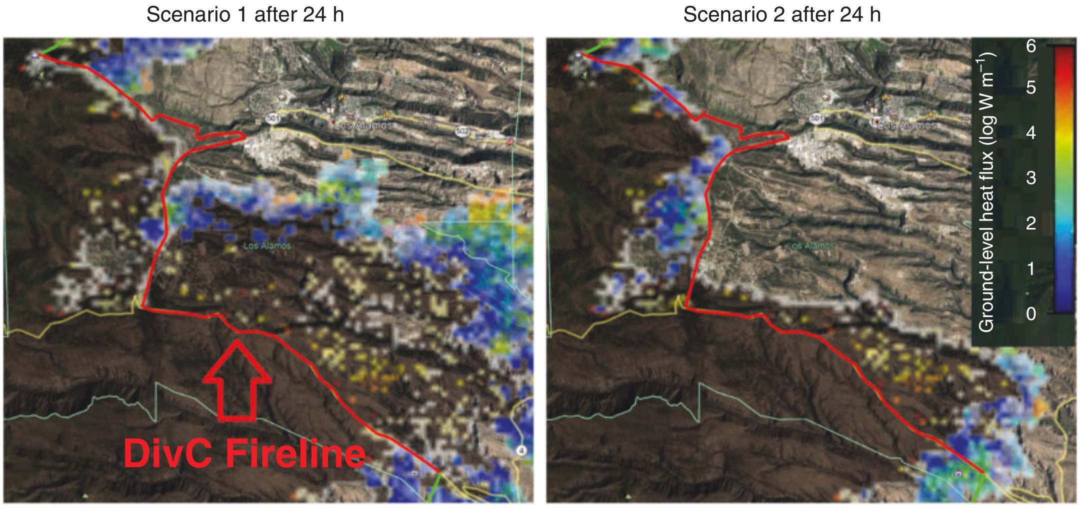

Fig. 6. WRF-SFIRE fire progression simulations of Scenarios 1 and 2 at Division C. The darker map regions indicate burned areas. Simulated Scenario 1 burned most of Los Alamos National Laboratory. Fuzzy blue area is active fire with heat flux indicated in the legend. Red line is Division C fire break line.

Table 2. Socioeconomic impacts of the scenarios compared (US$)

	Scenario 1	Scenario 2	Scenario 3	Difference 1 *v.* 3
Firefighters at risk	3 divisions	3 divisions	2 divisions	1 division
Los Alamos National Laboratory	Mostly burned	Mostly spared	Mostly spared	Catastrophic
24 h				
Property losses	$14 900 000	$14 900 000	$14 900 000	$0
Timber	$3 900 000	$3 200 000	$3 200 000	$700 000
48 h				
Property losses	$1 479 400 000	$962 000 000	$962 000 000	$517 400 000
Timber	$7 800 000	$6 200 000	$6 200 000	$1 600 000

highlights the socioeconomic impacts of the catastrophic outcome from Scenario 1.

After watching the video superimposed on the Las Conchas fire area, the IMT made no changes from their previous decisions for Divisions B through E in Scenario 2. However, they did express increased safety concerns for the team working to suppress fire along Scenario 2's Division A. The satellite information led to the conclusion that there might be more dangerous high-intensity fire activity along this perimeter than they expected when considering only the Scenario 1 information. This, combined with the rugged landscape and their experience with inconsistent canyon winds, led to the conclusion that fire activity along Division A could be less predictable than previously thought. Thus, they decided during the simulation exercise to remove the Division A crews and to halt suppression activities along this front. In a post-simulation report (R. McCrea and D. O'Brien, unpubl. data), the IMT noted that personnel should look further south and south-west for a safer ridge on which to establish fire suppression along a Division A line more distant from the fire.

Owing to wind direction, the modelled fire did not cross the initial Division A fire line during the 2-day simulation period regardless of whether fire suppression was simulated there. Thus, that fire line was unnecessary, and the MODIS input raised a valuable warning flag for firefighter safety and improved decision making in Scenario 3.

Other tangible and intangible losses not quantified in the experiment above are described in Supplementary material SC.

Discussion

The objective of this SEIA has been to address questions regarding the effect of satellite images and wildland fire modelling on IMT decision making for wildfire suppression. Did MODIS or WRF-SFIRE inputs alter the decisions of the IMT and enhance the socioeconomic impact of suppression actions on the Las Conchas fire? Although Table 2 comparing Scenarios 1, 2 and 3 demonstrates an abbreviated SEIA analysis, it highlights how decision-support tools can result in drastically different economic and social outcomes with serious consequences.

Scenario 3 showed that providing MODIS inputs to the IMT resulted in a safer decision along one of the firelines. Heightened awareness of firefighter safety based on MODIS data highlights the potential importance of satellite observations to the IMT's safety decisions.

As demonstrated herein, an SEIA can reveal more about values than we generally see in wildfire analyses rooted in VAR and

HVRA. Concerning the non-economic values threatened by Las Conchas, although we did not assign a monetary value to the loss of social-cultural values such as historical sites and sacred lands, our SEIA does recognise that a forest long considered sacred is more than acreage with estimated timber value, the damage to which we also measured for the economic side of our analysis.

Regarding the economic values shown in our SEIA, we focused on those resulting from losses to timber, private property and tourism. Both timber and private property losses from Las Conchas amounted to millions of dollars. Calculating these estimates was possible for this fire and could be done in the future, especially for the case of private property, with preplanning that includes the acquisition of cadastral maps from the relevant county(ies).

The Las Conchas fire final incident report indicates that no commercial structures were burned (National Wildfire Coordinating Group (NWCG) 2011). However, most natural disaster-related business losses and business failures do not occur during or immediately after the event, but later as a consequence of slow or failed recovery (Alesch *et al.* 2001). One of such losses is in tourism. Though tourism is an incomplete measure of the economic value of wilderness areas, its economic value can be estimated if we keep in mind that the economic value of protected forest land consists of both its recreational value and its preservation value (Godfrey and Christy 1991), even if tourism data do not capture preservation value directly – the value that non-visitors place on the option to visit wilderness in the future, and the value that both visitors and non-visitors place on the bequest of public lands to future generations (Loomis and Walsh 1991).

Tourism may increase or decrease after an area has been affected by wildfire (Ouellet 2018), but in general, it decreases. The Las Conchas fire undoubtedly affected tourism to the impacted Pueblos. (In New Mexico, the term Pueblo means a community of Native Americans.) Bandelier National Monument visitor counts were significantly lower in the 5 years after the Las Conchas fire compared with the prior 5 years (Tourism Economics 2017).

In Supplementary material SB, we describe how a wildfire's impact on tourism may be estimated specifically using Bandelier National Monument and New Mexico tourism data. We did not estimate the Las Conchas fire's entire tourism impact or its impact on the three scenarios for several reasons. Santa Clara Pueblo experienced reduced tourism and arts and crafts sales revenue (Chavarria 2015), but numerical data were not available. Pre-fire and post-fire tourist visitor data for the other Pueblos also were not available. However, Bandelier National Monument visitors' centre and its main attraction, prehistoric human habitation sites, were closed to visitors for 3 months (Bryan 2011). More than 60% of Bandelier National Monument was severely burned (National Park Service 2012). The bulk of the massive fire damages occurred 26–27 June 2011, the first 2 days of the Las Conchas fire, before the beginning of the 48-h time window of the scenarios analysed in the present paper. Therefore, our scenarios each simulated zero tourism losses caused during the 48-h simulation window.

Conclusion

Using a historical wildfire to test socioeconomic valuation methods

There are some advantages to using a large well-known historical fire to test socioeconomic valuation methods. A large volume of actual cost data is likely to be available. Archived IMT summaries may be found. Simulation results can be compared with known historical outcomes. The fire behaviour model may be tested, and parameters calibrated to more closely match the actual fire behaviour.

However, after a large historical fire, lawsuits and settlements obscure some of the relevant financial data. During the settlement process and after a judgment, some financial data may remain closely guarded and unavailable to researchers. Litigation awards and compromise settlement values may distort the actual value of damages, which are then less precisely comparable between different fires. Settlements also may obscure detail by aggregating multiple damage types into lump sums.

When simulating the impact of fire suppression actions, the ideal decision-makers are experienced forest and wildfire managers, but these experts may have prior knowledge of a well-known fire beyond the defined information limits of the experimental scenarios.

Quantifying wildfire benefits to the ecosystem

Wildfire SEIA involves trade-offs between the detailed comprehensive inventories of HVRAs and the simplification of the calculation interpretation of those results (Scott *et al.* 2013). One limitation of the present study is that we made no attempt to quantify the positive value of any wildfire impacts favourable to the ecosystem. Although not necessarily measurable in dollars, a fire response function could be designed to quantify the ecosystem gain resulting from a beneficial low-intensity fire, and to quantify ecosystem losses from a higher-intensity fire (Thompson *et al.* 2016*b*).

To avoid the potential ambiguities, changeable memory and new interpretations of results over time, future experimental design should require detailed fire suppression plans for each scenario contemporaneously written by the IMT instead of a later-written report.

Backfires as well as wildfires appear on satellite infrared images. IMT decision making in an experimental scenario using satellite information may vary depending on knowing which hotspots were uncontrolled and which were intentional tactical burn-outs. The IMT in a real fire should have more complete knowledge of prescribed burns in progress than we provided to the IMT in our simulated scenarios.

Effect of satellite observations on IMT decision making

The commanders' decisions without satellite observations were similar to what was done at the actual fire, including most of the selected firebreaks and of the parts of the fire perimeter where they would let the fire burn naturally.

The commanders used the additional information to infer where the fire was actively burning to reinforce their existing decisions and to make adjustments improving firefighters' safety. Economic impact was a secondary consideration.

The commanders treated satellite fire detections as indicators of potential hotspots, needing verification from the on-the-ground personnel or helicopter overflights. Limited spatial and particularly temporal resolution were pointed out as significant limitations of the satellite fire detection products in 2011. This observation is consistent with the fact that data from geostationary satellites, such as GOES-16, providing now fire products at nominal 2-km resolution every 5–15 min, are becoming increasingly popular in practice in spite of their lower spatial resolution and higher error rates (Hall *et al.* 2019).

Future enhancements to improve fire behaviour and impact modelling

Our model treated a structure as a total loss if fire was present, and as zero loss if fire did not reach that location. Adding a fire response function to generate fractional loss values for lower fire intensity may model property loss values more realistically.

The salvage value of burned timber may be more accurately modelled by adding a fire response function to reflect higher post-fire timber salvage values at lower fire intensity and lower values after higher intensity. A fuel model more detailed than Anderson (1982) combined with more precise values per area developed by timber experts local to the fire area could improve the valuation model's timber loss estimates.

Simulation of wildfire episodes starting from a large active fire's known perimeter could be improved. The simplified method used in this experiment treated the entire beginning fire perimeter as active fire. This condition was a realistic assumption in the early days before much of the Las Conchas fire perimeter was controlled. Most of the 29 June 2011 fire perimeter was hot. Simulation accuracy may be enhanced by modelling any known extinguished lengths of the beginning fire perimeter as cold.

Future research questions

Can satellite-informed modelling be used to more effectively allocate firefighting resources?

Can we estimate the value of more frequent infrared imaging satellite flyovers?

Conflicts of interest

The authors declare no conflicts of interest.

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