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Rapid-response tools and datasets for post-fire remediation: linking remote sensing and process-based hydrological models

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Abstract. Post-wildfire flooding and erosion can threaten lives, property and natural resources. Increased peak flows and sediment delivery due to the loss of surface vegetation cover and fire-induced changes in soil properties are of great concern to public safety. Burn severity maps derived from remote sensing data reflect fire-induced changes in vegetative cover and soil properties. Slope, soils, land cover and climate are also important factors that require consideration. Many modelling tools and datasets have been developed to assist remediation teams, but process-based and spatially explicit models are currently underutilised compared with simpler, lumped models because they are difficult to set up and require properly formatted spatial inputs. To facilitate the use of models in conjunction with remote sensing observations, we developed an online spatial database that rapidly generates properly formatted modelling datasets modified by user-supplied soil burn severity maps. Although assembling spatial model inputs can be both challenging and time-consuming, the methods we developed to rapidly update these inputs in response to a natural disaster are both simple and repeatable. Automating the creation of model inputs facilitates the wider use of more accurate, process-based models for spatially explicit predictions of post-fire erosion and runoff.

Additional keywords: database, forest fire, forestry, hazards, hydrology.

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Introduction

Prior preparation for emergency situations is critical to saving lives and mitigating damage to property, natural resources and livelihoods. Remote sensing plays a critical role in preparing for and responding to natural disasters (Tralli *et al.* 2005; Joyce *et al.* 2009). To better utilise Earth observations and fulfil a need for rapid assessment of burned watersheds, we developed an interactive modelling database that allows modellers to upload soil burn severity maps and within a few moments download spatial model inputs for process-based models. The database is operational and publicly available for the continental United States. Work is ongoing to improve datasets and add capabilities. The interface was created using open-source software to facilitate transfer of these capabilities to other countries with suitable soil and land-cover datasets.

Once the direct danger of an active wildfire has passed, land managers must rapidly assess the threat from runoff and erosion, now heightened owing to the loss of vegetation and litter from the forest floor and fire-induced changes in soil properties. Forests are highly valued as protectors of watersheds and reservoirs because the canopy and surface cover protect forest soils from erosion (Robichaud 2000; Moody and Martin 2001). After a wildfire, post-fire flooding and erosion can threaten lives, property and water supplies. Flooding after the 1996 Buffalo Creek Fire in Colorado resulted in the deaths of two people and sediment from this fire reduced Denver's municipal reservoir capacity by approximately a third (Agnew *et al.* 1997). The hazards of flooding due to increased runoff and mass movement events are of special concern near the wildland–urban interface, cultural sites, municipal water sources and sensitive habitats (Robichaud and Brown 2000; Moody and Martin 2001; Cannon *et al.* 2010; Moody *et al.* 2013). Similar problems are faced downstream of many other fires throughout the western USA, Canada, southern Europe and Australia. Planning the mitigation of these threats in the USA is undertaken by interdisciplinary Forest Service Burned Area Emergency Response (BAER) and Department of Interior Emergency Stabilization and Rehabilitation (ESR) teams who work diligently to estimate erosion and flood risk. These assessments are used to develop recommendations to mitigate increases in runoff and erosion (USDA and Forest Service 2004; US Department of the Interior 2006). Australia's state agencies follow a similar protocol (Robichaud *et al.* 2009) whereas Canadian provinces use smaller-team approaches (Robichaud and Ashmun 2013).

Complexities and uncertainties of erosion processes following wildfires and the high cost of mitigation (up to US$5000 per ha) require managers to make tough decisions when addressing post-fire effects. It is not uncommon for a single fire to require several million dollars to be spent on post-fire mitigation. Earth observations of burn severity are an integral component in remediation planning (Parsons *et al.* 2010), but there are also many modelling tools available (Renschler 2003; Elliot *et al.* 2006, 2010; Robichaud *et al.* 2007*a*; Elliot 2013). Spatially explicit and physically based models are currently underutilised as they require inputs representing the spatial distribution of burn severity, topography, vegetation and soil. These modelling tools help assess post-fire risk, prioritise expensive remediation treatments, predict impacts of treatments to justify costs, and increase understanding of fire effects on watersheds. Without a method for rapidly obtaining spatial inputs, it is infeasible for BAER and ESR teams to employ advanced watershed tools following large wildfires.

Our overall objective is to meet this data accessibility requirement by providing datasets and tools to support post-fire remediation. The novelty of our approach is we have prepared datasets so that changes resulting from wildfire can be rapidly incorporated. Our inspiration was to create a post-fire modelling database similar to LANDFIRE (LANDFIRE 2011) that supports multiple fire behaviour models including the Wildland Fire Decision Support System (Calkin *et al.* 2011). Work is under way to develop spatial web-based post-fire hydrology assessment tools (Frankenberger *et al.* 2011) that combine both the database and modelling tool similar to the Global Flood Monitoring System (GFMS) (Wu *et al.* 2014).

Post-fire erosion processes

Ground cover remaining after burning is a primary control on post-fire erosion rates (Benavides-Solorio and MacDonald 2005) and an essential input to post-fire erosion models. Wildfire reduces or removes the protective vegetation canopy and ground cover protecting forest soil; this increases the exposure of the soil surface to raindrop impact and wind. Normally, forest soils are covered with a protective duff layer (fresh and decomposing leaf litter and organic debris) (Elliot 2013), which protects soils by absorbing water and lengthening flow paths. Raindrop impact can destroy soil aggregation and detach sediment. When combined with shallow overland flow, this shallow runoff can transport fine soil particles and ash to macropores, decreasing infiltration rates and increasing runoff and erosion. The loss of surface cover also increases rill erosion, and on steep slopes can aggravate mass failure as surface woody material and root networks no longer stabilise them (Reid 2010). The loss of forest vegetation leads to decreased evapotranspiration, increased soil water content and decreased root strength, increasing the risk of runoff, flooding and landslides when soils are saturated (Reid 2010). Gases generated by burning duff can coalesce around soil particles, making soils hydrophobic, increasing risk of high runoff and surface erosion (DeBano 2000). The heat of the fire can also alter soil structure, making soil particles more easily detached or erodible (Certini 2005; Larsen *et al.* 2009).

Upland erosion frequently exceeds the ability of downstream channels to transport sediment delivered from burned hillslopes so river valleys and high-elevation reservoirs are frequent sites of considerable deposition. Much of the deposited sediment is routed downstream in years following the fire when stream flows are high (Smith *et al.* 2011; Elliot 2013). This sediment can be an important consideration for managing water resources within reservoirs (Tiedemann *et al.* 1979; Moody and Martin 2001; Neary *et al.* 2005; Smith *et al.* 2011; Santín *et al.* 2015). In the United States, US$26 million was spent on treating drinking water and dredging Strontia Springs Reservoir following wildfires in Colorado and US$190 million is planned for dredging reservoirs in California affected by sediment from the 2009 Station Fire (US Department of the Interior 2013).

The movement of soil material due to gravity alone is called dry ravel and it can be a substantial source of hillslope erosion in dry, steep environments following a wildfire (Wells 1981; Reid 2010). Normally, vegetation holds soil in place by roots and stems but, after a wildfire, these materials become dry and friable and are potentially free to move down slopes into channels and streams. Dry ravel typically occurs in dry environments on slopes greater than the angle of repose of the soil aggregates.

Earth observations of burn severity

Sudden changes to a watershed brought about by a large wildfire need to be quantified. The development of a burn severity map that reflects fire-induced changes in both vegetative cover and soil properties is of high priority. Many algorithms exist for mapping burn severity, but the most widely accepted is the differenced Normalized Burn Ratio (dNBR) algorithm (Key and Benson 2006), which has been shown to be well correlated with field measurements of burn severity (Bobbe *et al.* 2001; Robichaud *et al.* 2007*b*; Moody *et al.* 2016). dNBR maps and Burned Area Reflectance Classification (BARC) maps are generated using multispectral Earth Observation data (Parsons *et al.* 2010; RSAC 2011). BARC maps have four classes of post-fire vegetation condition derived by classifying dNBR maps and are often used as a preliminary map of vegetation burn severity. The Normalized Burn Ratio (NBR) is:

$$\mathrm{NBR} = (\mathrm{R_{NIR}} - \mathrm{R_{SWIR}})/(\mathrm{R_{NIR}} + \mathrm{R_{SWIR}}) \quad (1)$$

where $\mathrm{R_{NIR}}$ = satellite reflectance in near-infrared (NIR) (~0.75–0.9 μm) and $\mathrm{R_{SWIR}}$ = satellite reflectance in shortwave infrared (SWIR) (~2.09–2.35 μm).

The dNBR for a landscape is determined by calculating the change in NBR between a pre-fire and a post-fire image covering the same area:

$$\mathrm{dNBR} = \mathrm{NBR_{prefire}} - \mathrm{NBR_{postfire}} \quad (2)$$

After fire, reflectance in the NIR decreases owing to the loss of vegetation while reflectance in the SWIR increases. Changes in NBR provide a good estimate of change in vegetation canopy, and from that, an estimation of fire severity (Eqn 2). The algorithm assumes the dNBRs of unburned pixels are unchanged and that climatic and moisture conditions are similar for pre- and post-fire images. The dNBR is strongly positive for fire-stressed areas and strongly negative for regions experiencing enhanced regrowth. Grasslands often experience enhanced regrowth, which can be detected when the post-fire scene is recorded several months after the fire. The dNBR images created for BAER and ESR teams are typically collected immediately post-fire and are classified into unburned, low, moderate, and high burn severity by varying threshold levels. When possible, field measurements of soil and vegetation burn severity are collected to verify threshold levels as they can vary with vegetation (Elliot *et al.* 2006; Parsons *et al.* 2010). Lewis *et al.* (2006) compared burn severities predicted from remote sensing with observed soil burn severity on 183 plots and found the burn severity map matched 69% of the plots on the 2002 Hayman, Colorado, wildfire. When field measurements are not collected, the BARC map is the only estimate of burn severity available. When the dNBR map is adjusted based on soil conditions, it becomes a soil burn severity map (Fig. 1*a*). Landsat is typically the sensor of choice; however, multispectral aerial imagery and other imaging platforms with appropriate spectral bands such as SPOT (Satellite Pour l'Observation de la Terre), MODIS (Moderate Resolution Imaging Spectroradiometer), VIIRS (Visible Infrared Imaging Radiometer Suite) or Sentinal-2 can be used (Lentile *et al.* 2006).

Process-based and spatially explicit post-fire erosion modelling

BAER teams employ a wide variety of models. Our web database application is currently focused on providing support to Water Erosion Prediction Project (WEPP)-based models, but our spatial datasets have been used in other models. Spatial model inputs are provided in multiple raster formats, including GeoTIFF and ASCII grid, for ease of use and flexibility. The datasets can easily be used in other models and applications such as in agriculture or mining.

The Water Erosion Prediction Project (WEPP)

WEPP is a physically based hydrology and soil erosion model developed by an interagency team of scientists (Laflen *et al.* 1997). The surface hydrology component of WEPP utilises climate, topography, soil and vegetation properties to predict plant growth, residue decomposition and soil water balance on a daily time step, and infiltration, runoff and erosion on a storm-by-storm basis. WEPP then provides predictions of runoff, erosion and sediment delivery by event, month, year or average annual values for time periods ranging from a single storm to 999 years for either an individual hillslope or a watershed containing many hillslopes, channels and impoundments. A key advantage of WEPP is that it is process-based and, unlike empirical models, can be applied outside the region where it was developed (Elliot *et al.* 2010).

The WEPP model has a built-in stochastic weather generator, Cligen, which generates WEPP climate inputs from an extensive database of more than 2600 weather stations within the US (Flanagan and Nearing 1995). Cligen uses weather station parameter files to predict mean daily precipitation, minimum and maximum daily temperatures, mean daily solar radiation, and mean daily wind speed and direction. In the continental US, these statistics can be modified using Rock:Clime (Elliot *et al.* 1999) and PRISM's (Parameter-elevation Regressions on Independent Slopes Model) monthly precipitation database to account for spatial variation and elevation. PRISM uses digital elevation models (DEMs), climate data and other spatial datasets to generate grids of climate data at a resolution of 4 km^2 or finer (Daly *et al.* 1997). Rock:Clime is an online interface that accesses precipitation data from PRISM to interpolate between weather stations in order to improve the stochastic climate file. The interface allows users to adjust temperature by elevation using adiabatic lapse rate, a useful feature for remote mountainous terrain (Elliot 2004). Currently Rock:Clime has 30 international weather stations available in Europe, Asia, South America and Australia; the interface also supports the creation of new stations. Instructions are available to assist in the development of local climate files and required datasets are available online for most areas in the world. If more detailed climate data are available, the WEPP Windows interface has tools available to incorporate the information into a Cligen parameter file.

WEPP technology includes two versions: a hillslope version to estimate the distribution of erosion on a hillslope (under ~10 ha) and a watershed version that links hillslopes with channels and in-stream structures to estimate sediment delivery from small watersheds (under ~5 km^2). The WEPP model is a standalone FORTRAN program with ASCII files for all inputs and outputs and has been linked to numerous user-friendly interfaces. A Windows interface is available for both the watershed and hillslope versions of WEPP. The GeoWEPP *ArcGIS Wizard* to run the watershed version relies on the parameter database associated with the Windows interface, and users can build custom soil and vegetation files in the Windows interface to support GeoWEPP.

From the hillslopes, WEPP predicts total and peak surface runoff from each rainfall or snowmelt event (Flanagan and Nearing 1995), and daily shallow lateral flow to channels (Dun *et al.* 2009). WEPP watershed then routes total runoff and delivered sediment through the stream system, estimating additional sediment detachment or deposition in each channel segment. At the watershed outlet, daily runoff, net sediment delivery and an estimate of peak flow are calculated for each runoff event. From the daily values, the WEPP watershed version calculates average annual runoff and sediment delivery for the watershed. If requested and the length of run is long enough, return period values for daily precipitation amounts, sediment yields, daily runoff and peak runoff rate are calculated.

USDA Forest Service scientists have developed user-friendly online interfaces for the hillslope version to model unburned hillslopes and hillslopes following wildfire (Elliot *et al.* 1999; Elliot *et al.* 2006; Robichaud *et al.* 2007*a*). The two main hillslope tools available for post-fire analysis are Disturbed WEPP, which predicts average annual surface runoff and erosion values, and the Erosion Risk Management Tool (ERMiT), which predicts the probability associated with sediment delivery from a single runoff event (Elliot *et al.* 2006; Robichaud *et al.* 2007*a*). Both interfaces link land cover to vegetation and soil properties, so users need only select a land cover and soil texture. Disturbed WEPP has land cover for mature and young forests, skid trails, shrubs, good and poor grass communities, and low and high soil burn severity. Grasses

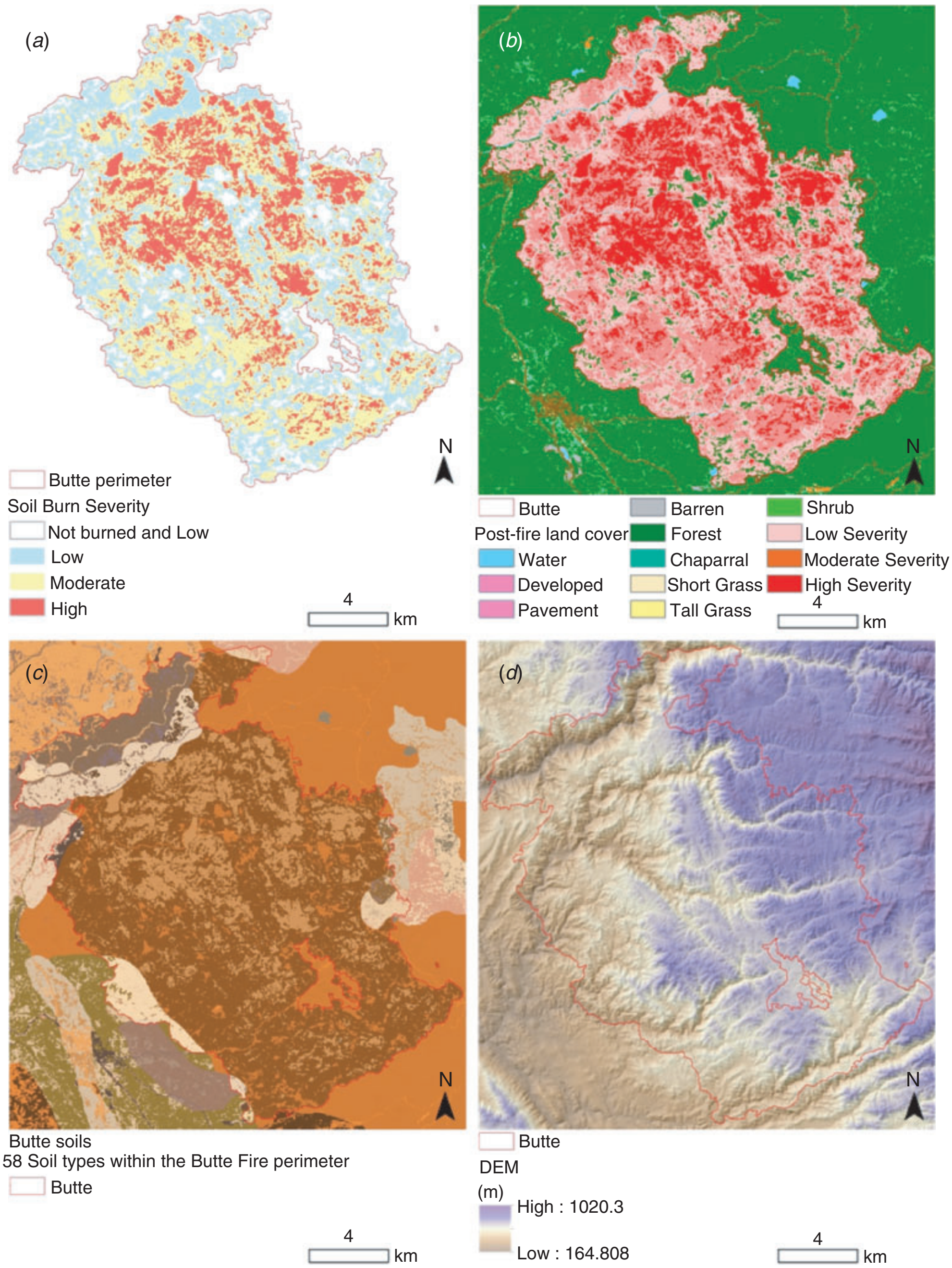

Fig. 1. Modelling datasets used in predicting the hydrological response of the 2015 Butte Fire that burned in California. (*a*) Soil burn severity map of the Butte Fire; the pre-fire image was collected by Landsat 8 on 6 September 2015 and the post-fire image was collected on 22 September 2015. (*b*) Post-fire land-cover map generated by the database for the Butte Fire. This map is a result of combining the soil burn severity map with the reclassified LANDFIRE Existing Vegetation Type (EVT) data. (*c*) Soils map generated by the database depicting soil files modified by the burned Butte Fire land-cover layer. To facilitate modelling, the corresponding WEPP (Water Erosion Prediction Project) soil parameter and linkage files are also provided by the online database. (*d*) The 30-m digital elevation model (DEM) downloaded for modelling the Butte Fire.

are divided into bunch and sod grasses to reflect their impact on effective hydrological conductivity – the rate water can pass into soil. In order to support BAER teams, spreadsheet tools for both ERMiT and Disturbed WEPP were created within Microsoft *Excel* to allow users to run multiple hillslope simulations (Elliot 2013).

The watershed version of WEPP is best run using a geographic information system (GIS) to analyse and manipulate required spatially explicit datasets. The most commonly used of these tools, GeoWEPP, was developed by Renschler (2003) for *ArcGIS*. GeoWEPP uses the topographic analysis software *TOPAZ* (Garbrecht and Martz 1999) to delineate watersheds and create topographic files needed to run WEPP. Typically, the same soil and vegetation parameter files are used in the online Disturbed WEPP interface, the Windows interfaces and the GIS tools.

Because of difficulties experienced by users in developing spatially distributed input files for GeoWEPP, an interagency team of scientists recently released an online GIS watershed tool specifically developed for forest conditions including wildfire (Frankenberger *et al.* 2011). This interface does not require any downloading or preprocessing of spatial data. In its current form, however, saving the outputs from a run or combining multiple runs for a large fire is awkward. It can only access soils that are part of the Natural Resources Conservation Service (NRCS) Soil Survey Geographic Database (SSURGO) and this coverage is incomplete, particularly in remote forest watersheds.

Uncertainties in predicting the hydrological response of burned watersheds are high and sources of uncertainty include model inputs: climate, topography, soil parameters and burn severity and land cover. Forecasting climate is especially problematic as precipitation amount and intensity are key drivers controlling post-fire runoff and erosion (Moody *et al.* 2013). The STATSGO (STATe Soil GeOgraphic) database and the higher-resolution SSURGO data often map multiple soils within one map unit; for the online database, the dominant soil was selected to represent each map unit. This introduces error in the modelling (Lathrop *et al.* 1995), but still represents the best available soil information. Because the variability associated with predicting post-fire erosion is quite high, predictions should be interpreted in this context (Larsen and MacDonald 2007; Robichaud *et al.* 2007*b*).

For post-wildfire modelling, the current scale of erosion analysis is by hillslope polygons (~5 ha). GeoWEPP selects dominant land cover and soil within each polygon and applies it to the entire hillslope when running in 'Watershed' mode (Renschler 2003; Flanagan *et al.* 2013). This is typically done for large-area analyses following wildfire. Zhang *et al.* (2009) found that shifting from a 30- to 10-m DEM tended to decrease sediment delivery, and attributed this change to increased deposition on toe slopes. They also found increasing resolution of the DEM from 10 to 6 m did not improve model performance. In 'Flowpath' mode, GeoWEPP predicts erosion for 100 points along flowpaths (Flanagan *et al.* 2013) and can include many different soils and burn severities. This feature is useful for targeting treatments to portions of hillslopes that have the greatest erosion risk, generally identified as steep upland shoulders of hillslopes (Elliot *et al.* 2006; Klein *et al.* 2015). 'Flowpath' mode requires considerably longer run times and results are intended to only provide hillslope erosion and not sediment delivery. Additional run time is usually a luxury not available for post-fire analysis, where results are needed quickly. As computer speeds increase, the finer-resolution runs become more feasible.

Ravel RAT

Ravel RAT (Risk Assessment Tool) is a physical model that applies classical soil mechanics and experimental observations to model dry ravel on steep slopes following a fire (Fu 2004). The motivation is to predict ravel movement, which helps managers assess potential stream channel loading from hillslopes that are steeper than the angle of repose. Ravel RAT predicts the behaviour and rates of dry ravel erosion and deposition. The simulation of ravel movement depends on the properties of the topography within the model domain, vegetation characteristics and the mechanical properties of the soil (e.g. friction coefficients). Long-term dry ravel processes are described with both theoretical calculations and empirical characterisation of post-fire ravel field observations. Primary inputs include a 10-m DEM, burn severity map, soil properties and pre-fire vegetation properties.

Empirical debris flow modelling

US Geological Survey (USGS) researchers have developed empirical post-fire debris flow models (Cannon *et al.* 2010) to predict the probability of debris flow occurrence and potential volume of material deposited in debris flow fans. Debris flows are one of the most dangerous consequences of rainfall on steep terrain burned by wildfire (Benda and Cundy 1990; Cannon *et al.* 2010). Basins that are prone to debris flows warrant special attention owing to the extreme risk they pose to life and property. Inputs for debris flow modelling include a DEM, delineation of sub-basins, storm intensity or total rainfall, clay fraction and liquid limit of sub-basin soils, and a burn severity map. Storm intensities and total rainfall can be obtained from gridded National Oceanic and Atmospheric Administration (NOAA) datasets in the USA (Bonnin *et al.* 2004) or regional databases.

Post-fire erosion web database application

To facilitate the operational use of spatially explicit and process-based models, we developed a web application that generates properly formatted model inputs. The application includes spatial tools to rapidly update input layers with user-supplied burn severity maps. Users may select a historical fire, upload a new soil burn severity map, or upload the output from a spatially explicit prediction of fire severity. Once uploaded, the soil burn severity map is combined with vegetation and soils datasets and then delivered to the user preformatted for modelling. Early application of the database included creating input for fuel planning projects using predictions of burn severity (Elliot *et al.* 2016). Modelling support for historical fires enables researchers and land managers to model cumulative watershed effects as well as develop, calibrate and validate models.

Our initial application supports WEPP-based models, but future improvements aim to include support for a dry ravel model, a set of empirical debris flow models and the Hillslope delineation toolbox to support online hillslope erosion interfaces. Improving the accessibility of both modelling capabilities and required datasets will lead to better assessment tools for forest managers, researchers and BAER teams. Model inputs produced by the web database application are designed to be used by both GeoWEPP and the online GIS WEPP tool. Support for additional models is provided by the flexibility in the format of the model inputs generated by the application. The first

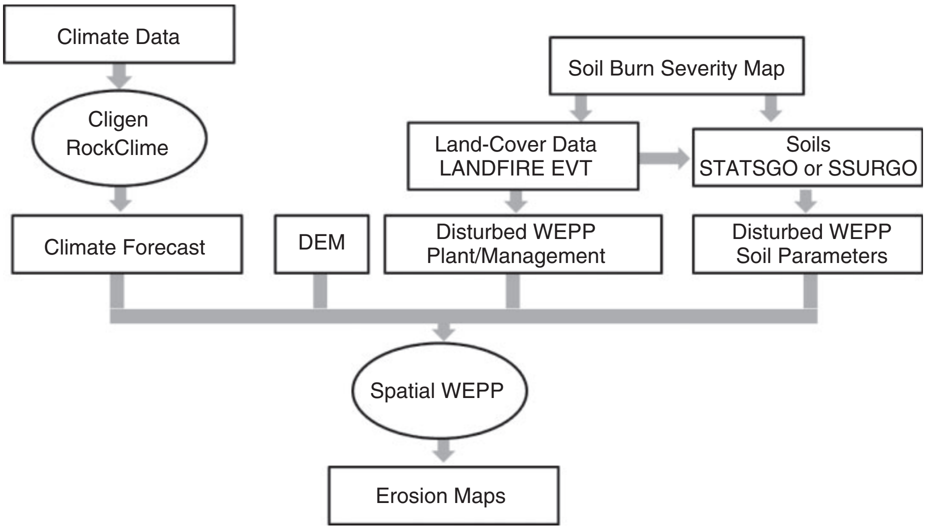

Fig. 2. A system flowchart to demonstrate model inputs and processing steps. Note that land cover is considered when creating soil input parameters; this step is important as even though grasses and shrublands may be completely consumed, they do not have enough fuel to create high-severity impacts on soils. DEM, digital elevation model; WEPP, Water Erosion Prediction Project.

non-WEPP database user downloaded spatial datasets from the 2002 Hayman Fire in Colorado, USA, to demonstrate post-fire erosion predictions with the SCIMAP pollution-risk mapping model developed in Europe (Reany 2013). For this and other purposes, we have developed support for an open-source, web-based application programming interface (API), which allows a remote computer to automatically query and download our spatial data products. User-uploaded burn severity maps from recent fires are kept private as a courtesy to respect homeowners impacted by wildfire. Uploaded burn severity maps are uniquely identified by a key, which can be shared or kept private by the uploading user.

Once a soil burn severity map is uploaded, it is combined with land-cover and soil datasets to generate the spatial model inputs needed for hydrological modelling of burn scars. Model inputs are created to represent the fire area both in its burned and unburned state. Users download three types of spatial layers: land cover, soils and a DEM that have been co-registered and projected specifically for hydrological modelling (Fig. 1*b*, *c* and *d*). Soil data are based on the SSURGO or STATSGO NRCS soil databases (USDA 1991; USDA Natural Resources Conservation Service 2014), the DEM is from the USGS (Gesch *et al.* 2002; Gesch 2007), and pre-fire land cover is derived from LANDFIRE Existing Vegetation Type (EVT) data (Rollins 2009; LANDFIRE 2011). The application delivers all the spatial inputs and parameter files needed for spatial WEPP models in seconds. Previously, assembling and formatting these data would have taken at least several hours, if not days.

Spatial data layers

DEM data from the USGS Seamless Data Warehouse serve as the base layers. The National Elevation Dataset is a 30-m DEM for the entire USA, with higher 10-m resolution available for the continental US (Gesch *et al.* 2002; Gesch 2007). Soils and land-cover data are projected to align with the DEM resolution selected by the database user. Global options for replicating the database include obtaining publicly available DEM data from NASA's Shuttle Radar Topography Mission (SRTM) as well as Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) products that currently provide global 30-m coverage at no cost (Land Processes Distributed Active Archive Center 2009).

Land cover within the database is derived from LANDFIRE EVT data (LANDFIRE 2011). Initial plans to use National Land Cover Data were modified after working on several collaborative fuel treatment projects involving fire behaviour modelling (Elliot *et al.* 2015). The EVT data allowed consistency between fire behaviour and hydrological modelling. EVT cover types were reclassified into Disturbed WEPP land-cover categories. When an uploaded burn severity map is used, it is combined with land cover data to create a burned land cover map. This map is then reclassified to create a burned soils layer (Fig. 2). This step is important as grasses and shrublands do not have enough fuel to create high-severity impacts on soils and clay-textured soils seldom become water-repellent. Planned future improvements include updating and improving WEPP plant-management input files to better reflect post-fire land-cover types. National land-cover maps are available for most countries and global land-cover maps are also available.

Soil layers and parameter files are derived from both the SSURGO and STATSGO datasets. SSURGO datasets contain the most detailed soil maps, but contain some data gaps (Miller and White 1998; USDA Natural Resources Conservation Service 2014). The STATSGO database has complete coverage and is a seamless layer derived from soil surveys conducted by the USDA (USDA 1991). The STATSGO database has a coarser spatial resolution than SSURGO. This lower resolution is not a great concern because in post-fire modelling, the erosion potential of soil is more a function of fire severity than of other soil properties (Elliot 2013). When soils are impacted by fire, the soil parameters are adjusted based on unburned land cover and low- or high-severity soil impacts. Research efforts are ongoing to improve post-fire hydrological models (Moody *et al.* 2013); therefore, the database is designed to allow soil parameters to be easily updated through a look-up table. To repeat this work outside the US, modellers will need to gather soil data needed to parameterise their selected model. In Europe, modellers have the European soil database available (Panagos 2006) and for regions without local soil maps, modellers could make use of the Harmonised World Soil Database (Nachtergaele *et al.* 2008).

To facilitate analysing historic fires, burn severity maps from the Monitoring Trends in Burn Severity project (MTBS) were preloaded into the application's database. MTBS is a partnership between the USGS EROS Center and the USDA Forest Service Remote Sensing Application Center to map burn severity and fire perimeters using the same dNBR algorithm used to create BARC maps for BAER Teams. These maps are not typically adjusted for post-fire soil conditions; therefore, modellers should use soil burn severity maps if they are available. The MTBS BARC maps are split into two categories: initial assessments created using satellite imagery from immediately after the fire and extended assessments created using imagery several months after the fire. Extended assessments are useful for predicting vegetation mortality and enhanced regrowth. Data limitations are important to remember when utilising MTBS data (Kolden *et al.* 2015). When using an extended assessment within the database, areas of enhanced regrowth are currently treated as unburned as initial burn severity is unknown. Fires occurring between 1984 and 2013 in the western US States larger than 400 ha (1000 acres) are included in the database. MTBS data are available online (Eidenshink *et al.* 2007; USDA and Department of the Interior 2009).

Database programming

Spatial data are stored using PostGIS (Obe and Hsu 2015; PostGIS 2016), a spatial database tool that extends the popular open-source database management system PostgreSQL (Momjian 2001; PostgreSQL 2016). The PostGIS extension is available at no cost, stable, robust and reasonably simple to use. Most of the transformations of the DEM, soil and land-cover datasets necessary for spatial WEPP models are performed directly in the database at the time the user makes a request, including spatial filtering, intersection and clipping, reclassification, resampling, raster algebra and reprojection. Spatial land-cover data are preformatted so that the classified burn severity maps can be simply added to the layer to generate burned land cover (Fig. 1*b*). This layer is then reclassified into a soil burn severity map and added to the soils layer. The application delivers WEPP soil parameter files in a zipped folder and WEPP linkage files that match land-cover and soils data with corresponding WEPP parameter files. The application produces DEM subsets and burned and unburned soil and land-cover layers as rasters on demand (~30–60 s over a broadband connection) for small fires (less than 20 km^2 or 2000 ha), and larger fires with longer computations may take a few minutes.

Results

The results are a web application with an expanding database that is currently online and capable of generating model inputs for predicting post-fire runoff and erosion in the continental US; the interim URL is: http://geodjango.mtri.org/geowepp/ (accessed 5 August 2016). Users can upload soil burn severity maps or select an area of interest and, moments later, download hydrological model inputs. The rapid incorporation of fire effects into modelling datasets allows more time to be devoted to running model scenarios and analysing model results (Fig. 3). The application has already been utilised in several fuels planning projects, two in California and one in Arizona. In the fall of 2014, BAER Teams in California utilised the application and model results on four wildfires.

Discussion and conclusion

Estimated runoff amounts, peak flows, upland erosion rates and sediment delivery are used to improve decision-making activities related to post-fire risk assessment and rehabilitation treatment selection. Fig. 3 shows a typical output from a series of GeoWEPP runs, highlighting hillslopes of greatest risk for erosion. BAER and ESR teams use these maps and site visits along with consideration of values at risk to target expensive remediation treatments.

Remote sensing does not provide a direct measurement of burn severity; however, studies have found the optical impacts are correlated with burn severity (Lewis *et al.* 2006; Hudak *et al.* 2007; Moody *et al.* 2016). In a study comparing Landsat-derived burn severity algorithms with field observations from 50 field sites from eight fires, Hudak *et al.* (2007) found that Landsat-derived dNBR maps were more accurate for mapping areas of high burn severity than for low or moderate severity. This is good news for BAER teams as identifying the high-severity burned areas is of most concern. Hudak *et al.* (2007) also observed that the dNBR maps were more closely correlated with post-fire vegetation than with post-fire soil conditions. The weaker correlation of dNBR with observed soil burn severity is tempered by recent hydrological field studies that have found the removal of surface cover (vegetation) to be the most significant factor in increased post-fire erosion and runoff (Larsen *et al.* 2009; Stoof *et al.* 2012; Hyde *et al.* 2015). These studies are important reminders that collecting post-fire observations of soil burn severity and remaining ground cover are important for parameterising WEPP runs. Remote sensing from satellite or aerial reconnaissance provides the only feasible option for assessing large burned areas in a timely fashion (Parsons *et al.* 2010). Multiple studies have shown that areas with high burn severity are at increased risk from erosion and runoff (Robichaud 2000; Benavides-Solorio and MacDonald 2005; Fernández and Vega 2015). The complex relationships between spatially and temporally varying burn severity and soil properties including hydrophobicity, hydraulic conductivity, erodibility and soil sealing have been identified as high-priority research topics (Moody *et al.* 2013). Work is ongoing to improve the predictive capabilities of models (Robichaud *et al.* 2007*a*; Fernández and Vega 2015) as there is a high degree of uncertainty associated with all erosion models.

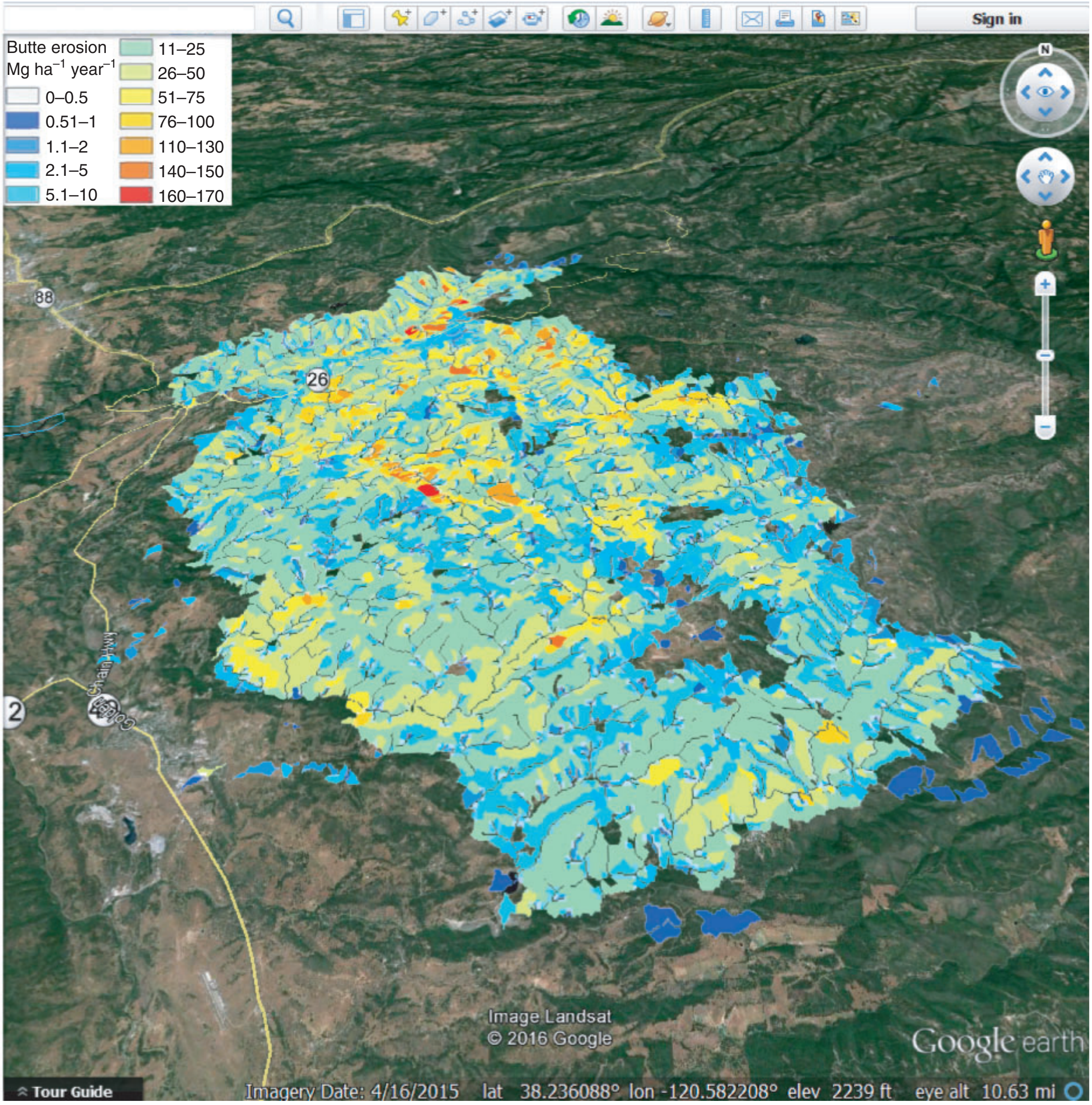

Fig. 3. Post-fire hillslope erosion predictions for the Butte Fire (28 700 ha) displayed in Google Earth. The view is tilted from the south to help visualise topography.

This uncertainty can be due to variability in soil erodibility, burn severity maps, and weather patterns (Brazier *et al.* 2000; Hudak *et al.* 2007; Robichaud *et al.* 2007*a*). In carefully planned and executed replicated rainfall simulation studies, it is common to find that the standard deviation of the erodibility is ~30% of the mean value. This means that there is approximately a 90% confidence interval that a given soil erodibility value is ±50% of the mean value. This means predicted soil erosion rates, are at best, within 50% of the mean. ERMiT (Robichaud *et al.* 2007*a*) was developed to address this variability. When applying GeoWEPP technology to post-wildfire landscapes, if there is sufficient time, a 50-year climate file may be used to ensure that variability within the climate is addressed. If time is limited, modellers may use a single storm or year of climate containing a known event, like a 10-year rainfall event (Elliot *et al.* 2006; Miller and Elliot 2015).

The utility of our methodology is clearly demonstrated with case studies from two recent wildfires. The 2011 Rock House Fire burned 127 500 ha in Presidio and Jeff Davis Counties, Texas, and impacted a small national historical site, Fort Davis, located in a small watershed called Hospital Canyon (217 ha). Even though the area that needed to be modelled was small, the time needed to reformat soil and vegetation data for modelling in GeoWEPP meant predictions were not completed in a timely fashion. In 2012, the High Park Fire burned 35 300 ha in Larimer County, Colorado; the spatial soil, land-cover and DEM layers

Fig. 4. The rapid response database in action on eight wildfires that burned in the western US in 2014–15 and on two fuels project in the Mokelumne watershed, California, and Flagstaff, Arizona.

were already prepared, along with a methodology for rapidly merging satellite-derived burn severity maps with the soil and vegetation data. The entire burn scar for the 2012 High Park Fire was modelled in less than 3 days, allowing the predictions to be available for operational use by the BAER team. These fires demonstrate the efficacy of preparing the tools and datasets before they are needed.

Operational use of the web database application

Using our web application, we were able to support BAER Teams on eight fires that burned in 2014 and 2015 in California (CA), Idaho (ID) and Oregon (OR) (Fig. 4; the French, CA; Happy Camp, CA; Silverado, CA; King, CA, Clearwater complexes, ID; Canyon Creek, OR; Valley, CA, and Butte, CA, fires). The French (5600 ha) and Silverado (390 ha) fires were small; therefore, predictions of post-fire erosion and runoff could be generated in GeoWEPP within just a few hours. The larger King (39 500 ha), Happy Camp (54 200 ha), Valley (30 800 ha) and Butte (28 700 ha) fires required 1 to 2 days to complete a single modelling scenario.

Silverado Canyon has a history of debris flows and significant flooding, with fatalities reported for events in 1969 and 2005 (Gallegos 2014). Because of this history and the proximity of values at risk, in this case people and their homes, the BAER teams on the Silverado Fire were especially diligent and several different models and scenarios were used to assess risk. Spatial WEPP modelling was used to predict both erosion and potential peak runoff flows at the base of the Silverado Trail watershed. Multiple scenarios were carried out to estimate the hydrological impact the fire would have on peak flow rates for storms with 2-, 5-, 10- and 25-year return intervals. The effects of mulching the treatable portions of the watershed were modelled at two different rates – 2.5 and 3.7 Mg ha^{-1} – in order to estimate the effectiveness of the treatment in mitigating peak flows. The BAER team concluded the largest risk was posed by the potential for debris flows in the basin (Gallegos 2014).

The King Fire BAER team utilised several modelling scenarios including predictions of average first-year post-fire erosion with 25 years of climate (Fig. 5) and post-fire erosion from a single 5-year storm event. Using our web application,

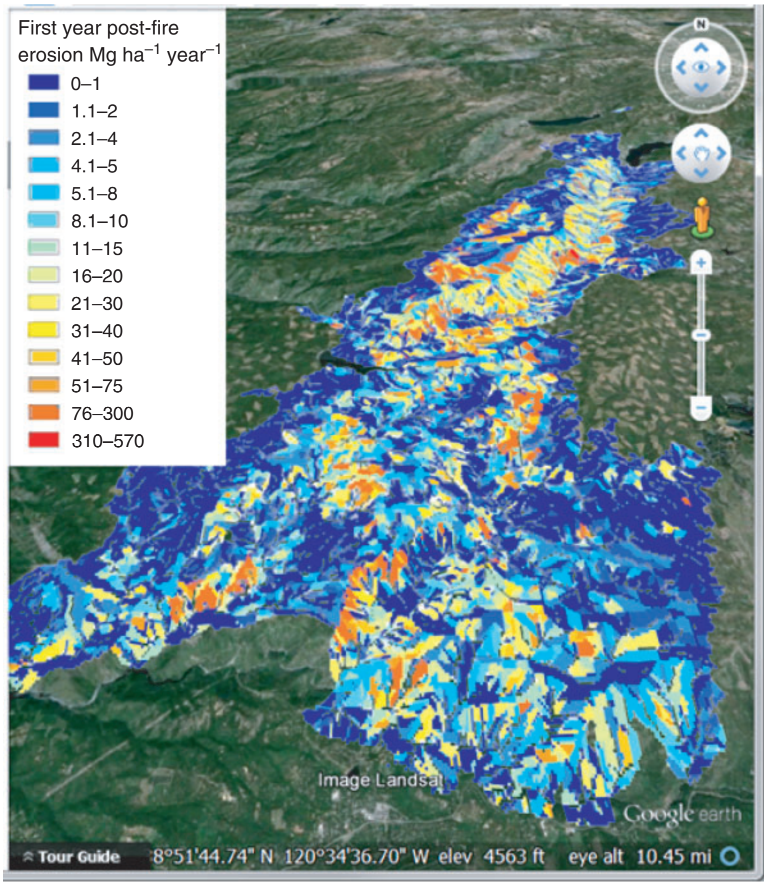

Fig. 5. Post-fire hillslope erosion predictions for the King Fire (39 500 ha) displayed in Google Earth. The view is tilted from the south to help visualise topography.

spatial DEM, land cover and soils data were created in seconds. For both climate scenarios, the burned watersheds were modelled in both pre- and post-fire state in order to estimate additional erosion due to the fire. Once initial modelling was completed, the BAER team proposed several mulching treatments expected to increase ground cover to 72%. Effects of increased ground cover due to mulching were then modelled and results were used to target more than US$1 million in mulching. Predictions also helped justify treatment costs, some of which were paid for by the Sacramento Municipal Utility District to protect a hydroelectric and water supply reservoir downstream of the fire (Jeff TenPas, USFS Region 5, pers. comm., 10 April 2015).

Assembling datasets needed to run spatially explicit erosion models can be a daunting task even without time constraints. Soil scientists, hydrologists and other BAER team specialists do not always possess the skills and knowledge needed to rapidly integrate remote sensing imagery into models. Therefore, preparing the required input data ahead of time makes sense. A manual is included on our website to guide users through the modelling process. Work will be ongoing in the next year to add additional support for dry ravel (Fig. 6) and debris flow modelling. Once completed, the application will be transferred to our Federal partners. Future development efforts could include the creation of look-up tables to reformat inputs for

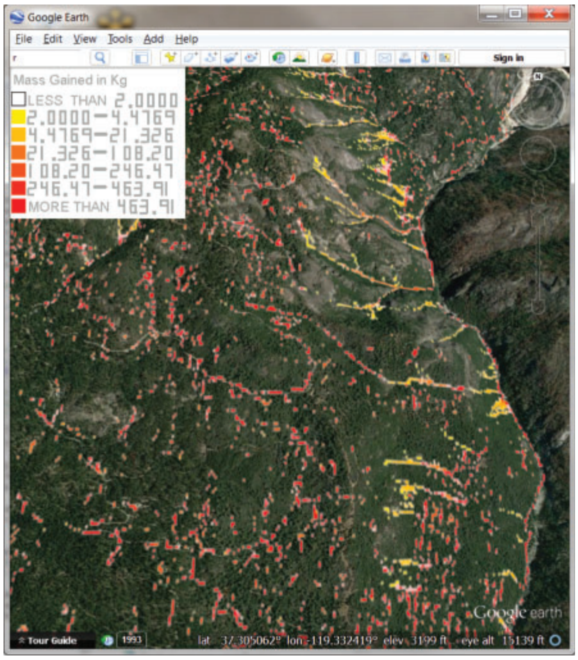

Fig. 6. Dry ravel predictions for the French Fire (5600 ha) displayed in Google Earth. The view is tilted from the south to help visualise topography.

other models. The database can easily support other applications such as for agriculture or mining as modellers can download preformatted data without modifying inputs for fire. We are open to expanding or sharing the technology with other countries. Our vision is that advanced GIS surface erosion and mass-failure prediction tools will be readily available for post-fire analysis using spatial information from a single online site.

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