INCLUDING WATER CONTAMINATION RISK FROM ASH INTO THE DECISION-MAKING PROCESS AFTER WILDFIRES: A NEW TOOL FOR RESEARCHERS AND END-USERS

Jonay Neris*[1], William J Elliot[2], Stefan H Doerr[1], Peter R Robichaud[2], Cristina Santin[1], Gary Sheridan[3]

[1] Department of Geography, College of Science, Swansea University, Swansea, UK.

[2] U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. Moscow, Idaho, USA.

[3] University of Melbourne, Melbourne,Victoria, Australia.

Abstract

Ash produced by wildfires is enriched in nutrients and other potential pollutants that can reach and contaminate water bodies through fire-enhanced water erosion events. Displace ash can lead to drinking-water restrictions and substantial treatments costs as experienced after fires for (e.g) for Belfast, Canberra, Denver, Fort McMurray. Recent fires in the USA, UK and Sweden (2018) have also highlighted once more that wildfires can also affect human-made structures, areas contaminated by industrial activity, and forests that rarely burn, aggravating and extending the risk of water contamination by wildfire ash. However, ash-induced risk assessment is usually not explicitly incorporated into the decision-making processes before, during or after fire events. One reason for this is that current hydrologic and erosion models lack capabilities to predict ash delivery and the subsequent contamination risk.

To fill this research and management gap, a prototype model that adds capabilities to predict ash delivery and potential contamination risk to the widely-used Water Erosion Prediction Project model (WEPP) is being developed. The prototype integrates and quantifies the main processes that affect ash in the ecosystem: from its production and composition based on fuel consumption and fuel characteristics to its transport by wind or water supported by meteorological simulations. The Normalized Wildfire Ash Index (NWAI) that predicts ash production based on fuel consumption information from Landsat imagery is used to quantify the initial ash loads after a fire. Climate, runoff, and erosion predictions by WEPP are used as drivers to predict ash temporal availability and transport across the landscape. The potential water contamination risk is determined by integrating these factors and ash composition information (concentration of nutrients and other potential pollutants) obtained from the combination of fuel type and burn severity data.

To calibrate and validate the model for key vulnerable environments, data on ash chemical and physical properties, and field data on ash loads and delivery via runoff and erosion are currently being obtained from wildfire-affected areas in Australia, USA, UK, and Spain. Once calibrated and validated for specific scenarios, the model will support managers in anticipating water contamination risks from fire and implementing effective mitigation treatments to protect drinking water supplies and aquatic ecosystems from ash contamination.

Introduction

The current and projected future decline in fresh water availability in many regions around the world has given rise to an increased focus on water contamination risks (World Economic Forum

2015). Fire-prone and fire-managed land cover types such as forests, grasslands or peatlands provide 60% of the water supply for the world's largest 100 cities (c. 750 Mill. people in total) (Martin 2016) and every year wildland fires burn more than 350 Mill. hectares of the global land surface (twice the size of the UK). The occurrence of fire is expected to increase with climate- and land management changes in many regions. Ash from vegetation fires is often rich in pollutants and very susceptible to movement during fire-enhanced water erosion events (Bodì *et al.* 2014; Smith *et al.* 2011). Additionally, recent events in USA, UK and Sweden have highlighted once more that wildfires can also affect human-made structures, areas contaminated by industrial activity, and forests that rarely burn, aggravating and extending the risk of water contamination by wildfire ash.

Previous studies have reported ash loads >190 t ha^{-1} after some severe fires in the USA (Martin 2016) and as much as four tonnes of phosphorous available for release to a single water supply reservoir after a severe fire in Australia (Santín *et al.* 2015). Ash delivery to water bodies after fires followed by intense rainfall has led to levels of up to 120 times the guideline limit of carcinogenic compounds, and toxic algal blooms in reservoirs in Australia (Smith *et al.* 2011) and the USA (Abraham *et al.* 2017). Fires in UK peatlands have led to the release of heavy metals accumulated through past industrial activity (Davies *et al.* 2016).

These impacts on water quality have caused drinking-water restrictions affecting large metropolitan areas (e.g. Denver 1996 & 2002, 2.5 Mill. people; Canberra 2003, 0.4 Mill. people; and Belfast 2011, 1.2 Mill. people) and substantial direct costs to restore ecosystem services and protect human health (e.g. £21 Mill. Denver, £23 Mill. Canberra, £3 Mill. Belfast) (Martin 2016). Preventing or reducing such impacts and costs depends on the ability to anticipate ash delivery and take related mitigating actions, such as stabilization of soils in the hillslopes, and significantly reduce the risk of ash production in vulnerable areas through fuel reduction practices and creation of fire breaks (Nunes *et al.* 2018). However, no models currently exist that allow prediction of ash delivery and contamination risk following fire, presenting a major knowledge and capability gap. Here we report on a project aimed to address this critical gap, supported by interdisciplinary collaboration with stakeholders from the land- and water management sectors through the UK's Natural Environment Research Council (NERC) funded project Fire&Water.

Material and methods

Producing an effective ash contamination risk model is challenging as it requires knowledge of (i) the amount of ash available to be transported, (ii) its transport behaviour and, (iii) its contamination potential. We have developed a proof-of-concept model built on existing knowledge such as: (a) the Normalized Wildfire Ash Index (NWAI), that predicts ash production for different fuels loads and fire severities (Chafer *et al.* 2016), (b) total analysis and leaching methods to quantify the total and water-extractable potential contaminants in ash, which enabled prediction of maximum reservoir contamination risk (Santín *et al.* 2015), and (c) a recently developed model to predict settling behaviour of ash in reservoirs that provides estimates of the duration of water quality impacts once ash enters a reservoir (Schärer *et al.* 2017).

To predict ash transport by water in the landscape, we combine widely-used methodologies to evaluate soil erosion by water (silt fences and rainfall simulations) with a novel tracing technique that enable us to disentangle ash and soil when mixed in the eroded sediments. The methodology is based on the differences in carbon composition between ash and mineral soils found in our previous work (Neris *et al.* 2017). This tracing approach allows us to convert data on sediment transport (ash+soil combined) into data on ash transport, which is necessary for calibrating and validating the ash delivery risk model. The Water Erosion Prediction Project (WEPP) (Laflen *et al.* 1997) supports the prediction of runoff and sediment production needed to generate values of ash transport.

This research program is currently being implemented through case studies in Australia, UK, USA, and Spain in order to calibrate the model using field data from vulnerable environments. Additionally, an initial calibration and validation test has been performed using existing laboratory data. Briefly, rainfall and inflow experiments were conducted on a flume (3.7 x 0.3 m^2; 40% slope) of burned soil covered with two different ash types representative of low and high burn severities (for further details on the flume experiments please see Prats *et al.* (2018)). Runoff production during the flume runs were simulated using WEPP and converted to ash delivery using the data obtained using the tracing technique stated above. The Nash-Sutcliffe Efficiency Index (Nash and Sutcliffe 1970) was used to test the validity of the results obtained by the calibrated ash delivery model. The *Results* section below focuses on this test and the outcomes of a case-study based on the fire-induced water contamination event occurred in 2003 to one of the water systems that supplies fresh-water to the Cotter fresh-water supply system for Canberra. For this case-study, we predicted Fe concentration, one of the main issues that led to the declaration of this system as being unfit for direct use, for different return periods using our model and compared those values to the Australian Fe guideline value in drinking-water (0.3 mg L^{-1}) to test its performance. Although based on a real event, this case-study is built on both observed data and parameter values estimated from the literature used if specific relevant information was not available. Thus, the aim of this case-study was to evaluate the functioning of the proof-of-concept ash model and its potential in guiding end-users in predicting water contamination risk.

Results and discussion

Disentangling soil and ash in sediments

In a flume study Prats *et al.* (2018) reported organic carbon content in *in situ* soil samples, ash samples that had been spread on the plot, and eroded sediment samples (*in situ* soils + ash) surface prior to rainfall simulation. Total organic carbon (TOC) of the ash samples was higher (86%) than that of sediment samples (6.6%) and soil samples (0.9%) used to perform the flume experiment. TOC of the soil samples was the lowest of the three materials evaluated, whereas the TOC of the sediments fell between the concentrations found for ash and soil samples as expected, since sediments are a mixture of the ash and soils transported by the runoff (Figure 1A). This finding enabled us to use TOC as a simple tracer for ash quantification in the sediments obtained during each of the flume experiment runs.

A B

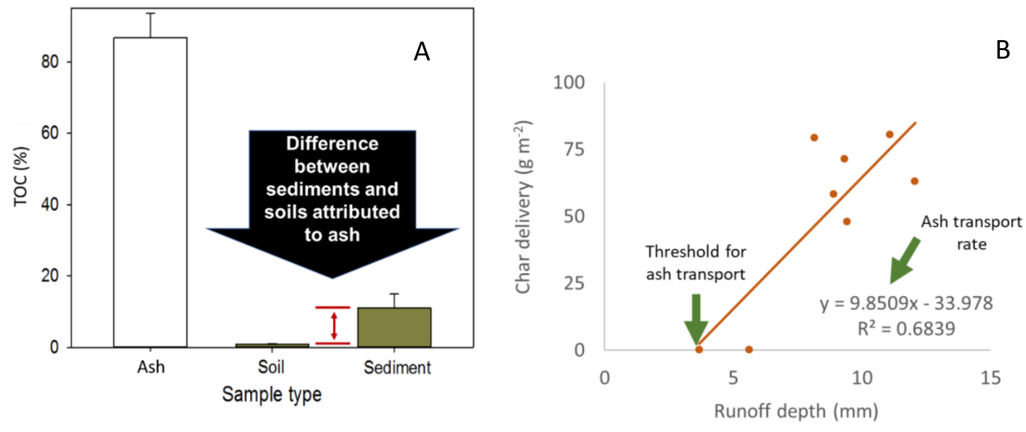

Figure 1: (A): TOC content of ash, soil and the sediments samples eroded from both layers in the laboratory flume experiment; (B): Calculating ash transport parameters (runoff threshold and ash transport rate) for the ash produced by a high severity burn.

Runoff produced during the flume runs was modelled using WEPP and estimations of runoff depth obtained for each run. The calibration and validation process showed that the ash transport model produced reasonable predictions of ash delivery with NSE values greater than 0.9 for transport of ash from both high and low severity burns. A simple linear regression between the runoff depth calculated by WEPP and the calculated ash delivery in the sediments for each flume run was then used to calculate for each ash type (i) the runoff threshold to produce ash delivery as the x-intercept of the regression equation (3.4 mm of runoff), and (ii) the ash transport rate as the slope of that equation (98.5 kg ha^{-1} mm^{-1})(Figure 1B).

The ash transport parameter values obtained were used in combination with the WEPP runoff predictions for each flume run to estimate ash content in the sediments collected. The calibration and validation process showed a good performance of the model when predicting ash delivery, with reasonable NSE values higher than 0.6 for the delivery of ash from high severity burns and higher than 0.8 for the transport of ash from low severity burns.

The Canberra 2003 case-study

In 2003, a wildfire occurred above the Cotter Reservoir, a major source of water for Canberra. Some details of that fire along with the conditions used for predicting Fe concentration for different return periods in the Cotter system are presented in Table 1.

Table 1: Simulation scenario for the Canberra 2003 water contamination event

Parameter	Value	Source
Fire-affected area	164,000 ha	Internet
Fire-affected area draining into Cotter	1/3	Estimated
Burn severity	High	Estimated
Cotter water supply system volume	40.000 m^3	Internet
Runoff threshold for ash delivery	3.4 mm	Flume experiment test
Ash delivery rate	98.5 kg ha^{-1} mm^{-1}	Flume experiment test
Soluble Fe in eucalyptus ash	3.2 mg kg^{-1}	Santín *et al.* (2015)
Fe entrapped in the network	50%	Assumed
Fe distribution in the reservoir	Equally distributed	Assumed
Australian Fe guideline value in drinking-water	0.3 mg L^{-1}	Australian Drinking Water Guidelines

The online Disturbed WEPP interface (Elliot 2004) was used to estimate runoff and sediment delivery from a typical eroded hillslope in the burned watershed. As shown in figure 2, WEPP provided simulated results for annual surface runoff production (mm) (Step 1, green boxes) that were sequentially converted to: (i) ash delivery (t ha^{-1}) using the runoff threshold for ash delivery (mm) and the ash delivery rate values obtained for the flume experiment test (t ha^{-1} mm^{-1}) (Step 2), (ii) Fe delivery (kg ha^{-1}) using the values of soluble Fe in ash samples (mg kg^{-1}) produced from eucalyptus forest reported by Santin et al. 2015 (Step 3) and, (iii) Fe concentration in the reservoir based on the burned area draining into the reservoir, the volume of the reservoir, the amount of Fe entrained and held in the network before reaching the reservoir, and the distribution of the potential contaminant in the reservoir (Step 4).

Return period analysis based on 100 years of climate

					(Step 2)	(Step 3)	(Step 4)
Return Period	Precipitation (mm)	Runoff (mm)	Erosion (t ha^{-1})	Sediment (t ha^{-1})	Ash delivery (t ha^{-1})	Fe delivery (kg ha^{-1})	[Fe] water (mg L^{-1})
100 year	1466.30	393.58	141.32	141.3168	23.84	0.08	5.4
50 year	1416.70	331.15	136.45	136.4463	18.17	0.06	4.1
20 year	1130.70	239.18	95.93	95.9296	9.21	0.04	2.8
10 year	1072.00	194.01	86.88	86.8770	7.32	0.03	2.0
5 year	979.50	154.58	63.73	63.7274	4.10	0.02	1.3
Average	810.49	115.84	47.82	47.8200	2.28	0.01	0.8

Figure 2: on-line disturbed WEPP output (green boxes) showing the additional steps (orange boxes) to generate the ash contamination risk results.

All the predicted concentrations of Fe in water for the different return periods evaluated by the model were greater than the Australian Fe guideline value in drinking-water (0.3 mg L^{-1}) and, thus, the model predicted that the water was unfit for direct use after the runoff events occurred in the post-fire period for the used scenario conditions. The same conclusion was reached by the water supply managers following the 2003 fire.

Conclusions

Our novel tool for incorporating water contamination risk from ash into the decision-making process after wildfires is showing very promising preliminary results. The proposed ash tracing technique based on the differences in TOC composition between ash and soil was able to quantify ash in sediments in a test using available laboratory data and is now ready for testing against field data. The proof-of-concept model predicted levels of Fe in the Cotter water system greater than the Australian guideline values for drinking water and, thus, was capable of anticipating the fresh-water contamination event occurred in Canberra 2003. Supported by these results, we are currently undertaking international field campaigns aimed at collecting field data on sediment delivery after wildfires that, together with the tracing technique described here, will enable us to calibrate and validate our ash contamination risk model for vulnerable ecosystems and support land managers in mitigating the impact of ash on water quality in the post-fire period.

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