Impacts of a wildfire on soil organic carbon in Warrumbungle National Park, Australia

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A wildfire in the Warrumbungle Range in January 2013 burnt 56,290 ha of forest land, 72% of it at high-extreme severity. We investigated the effects of fire on soil organic carbon (SOC), soil carbon fractions (Particulate Organic Carbon (POC), Humus Organic Carbon (HOC) and Resistant Organic Carbon (ROC)) at 64 sites stratified according to geology and fire severity across Warrumbungle National Park. Statistical models were used to identify the main factors controlling the soil chemical parameters and we spatially extrapolated results based on these main factors to estimate the overall impacts of the fire.

Statistical models indicated that the key effects on SOC were fire severity and geology/soil type. SOC declined with increasing fire severity − topsoil SOC in low severity sites was 14% lower than unburnt sites, and severely burnt sites were 54% lower than unburnt. There were also significant differences in SOC fractions between the different geology/soil types. These results were also reflected in N and pH changes. The highest SOC values were from unburnt volcanic topsoils. Sandier and especially sandstone-derived soils had less SOC irrespective of the fire severity class. The lowest SOC values were from severely burnt sandstone ridges, where most of the remaining SOC occurs as ROC (including charcoal). Site data was classified according to a fire severity map and geological mapping, and class averages spatially extrapolated to obtain an estimate of the amounts of SOC lost due to the fire. An estimated 1.52 Mt (26.99 t/ha) of SOC was lost over the fire ground to 10 cm. SOC levels in unburnt control sites are much higher than averages in the generally cleared central west of NSW, thus underlining the importance of forested ecosystems in carbon sequestration in soils, and of Warrumbungle National Park with its high proportion of trachytic clayey soils in particular.

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KEYWORDS: carbon fractions, soil organic carbon, wildfire impacts.

INTRODUCTION

On 12 January 2013, a fire started in Warrumbungle National Park (WNP), in the North West Slopes region of New South Wales, and burnt out of control. When extinguished about two weeks later, the fire had burnt 56,290 ha, including 95% of the 23,312 ha national park (Coroners Court of NSW 2015). Seventy-two per cent of the park burnt under high or extreme fire severity, with substantial losses of groundcover and SOC. Furthermore, on 1 February, an intense storm from the southwest caused massive erosion (Yu 2015; Zhu et al. 2018; Yang et al. 2018; Tulau et al. 2019a).

SOC is an important soil parameter which controls key soil chemical, physical and biological properties and hence soil function and biodiversity. It aids in the development of soil aggregates, it improves soil structure, the availability of nutrients and soil moisture, and it increases soil biodiversity and general ecosystem productivity (Murphy 2014). At a catchment scale, losses in SOC also can affect the hydrologic responses of catchments by reducing the amount of water that may be stored in topsoils, and therefore increasing runoff-infiltration ratios, which affects soil erosion rates and the geomorphic responses of drainage lines (Shakesby and Doerr 2006).

Soil organic matter (SOM) is particularly susceptible to wildfire, due to the relatively low temperatures of volatilisation and combustion for carbon (Gonzalez-Perez et al. 2004). Inorganic carbon may then be released from the ecosystem by convection and other pathways (DeBano et al. 1990). Fire can also have significant impacts on the quantities (Homann et al. 2011) and forms (Hatton and Zabowski 2009) of the remaining SOC, producing an increase in pyrogenic forms that are largely resistant to degradation, referred to as resistant (or recalcitrant) organic carbon (ROC) (Hobley et al. 2013).

The amount of SOC volatilised and oxidised is related to both direct radiant heat and to increased soil temperature, and therefore to fire intensity and severity (Giovannini and Lucchesi 1997; Hille & den Ouden 2005; Homann et al. 2011). The penetration of thermal energy into the soil is affected by soil characteristics such as texture and mineralogy, bulk density, pore size distribution, and soil moisture contents (Hobley et al. 2016). Dry soils, sandy soils, and soils with low bulk density have a lower specific heat and greater thermal conductivity than moist soils, clay soils and soils with higher bulk density. Generally however, even high intensity fires typically heat only the uppermost 100 mm of soil (DeBano 2000), with steep temperature gradients down the profile so that temperatures at 50 mm in the mineral soil rarely exceed 150^{o}C (DeBano 2000, Certini 2005).

Nevertheless, in comparison to lower intensity burns, which typically result in lower losses of carbon (Volkova et al. 2014), high severity wildfires can impact on the carbon storage of ecosystems and soils for decades to centuries (Bowd et al. 2019).

Despite the importance of fire, detailed studies of the magnitude of SOC losses, transformations and impacts from wildfire are lacking in the Australian context, an omission that is of some concern because the impacts of wildfires are particularly marked in many Australian soils, where a large proportion of the SOC is located in the relatively thin O and A horizons (Gray et al. 2016). In the absence of fire, the size of the SOC pool is largely determined by a range of site factors. Climatic factors include annual rainfall and its seasonal distribution, including whether there is a pronounced dry season. Aspect, slope and topographic position on the slope affect site wetness and soil moisture regimes. In terms of soil type, the key factors are the particle size distribution and soil structure. Clay is correlated with increased water holding capacity of soils and therefore biological activity and the accumulation and cycling of SOM (Wiesmeier et al. 2019). Land use factors include fire-related factors such as the length of time since fire – generally, the longer the period without fire, the greater the size of the nutrient pool contained in the litter and O/A layers (Adams and Attiwill 2011).

The Warrumbungles fire provided an opportunity to examine the impacts of a single large fire of varying severity on SOC, N and pH at a range of sites and soil types. This paper therefore aims to: quantify the total amount of SOC in control (or unburnt) soils, including SOC-depth profiles; quantify the impacts of different fire severities on SOC and SOC fractions; identify the major variables that explain the spatial distribution of SOC; and quantify the total amount of SOC lost from the ecosystem by the fire.

METHODS

Study Area

The study area is based on the Warrumbungle fire footprint and adjacent unburnt areas of WNP in the North West Slopes region of NSW (Figure 1). The area is approximately 360 km northwest of Sydney and approximately 25 km west of Coonabarabran.

The Warrumbungle Range is the remnant of a Neogene shield volcanic complex, rising to 1,206 m at Mount Exmouth, and punctuated by lava domes, plugs and dykes of the Warrumbungle Volcanics (Troedson and Bull 2018). Trachytes are a common rock type, with rhyolites, basalts, and volcaniclastics. In the central part of the park, Wambelong Creek has eroded a central valley, where Jurassic sandstones are exposed. Generally, the Warrumbungle Volcanics overlaid Pilliga Sandstone; in parts of the northern section of the park the volcanics overlie Keelindi Beds.

The climate is characterized by hot, usually humid summers and mild to cool winters. The mean maximum temperature at Coonabarabran Airport Automatic Weather Station (Bureau of Meteorology [BoM] station 064017) in January is 31°C, the mean minimum in July is 5°C. The mean annual rainfall at Westmount (BoM station 064046), on the eastern boundary of the park, is 1,034 mm.

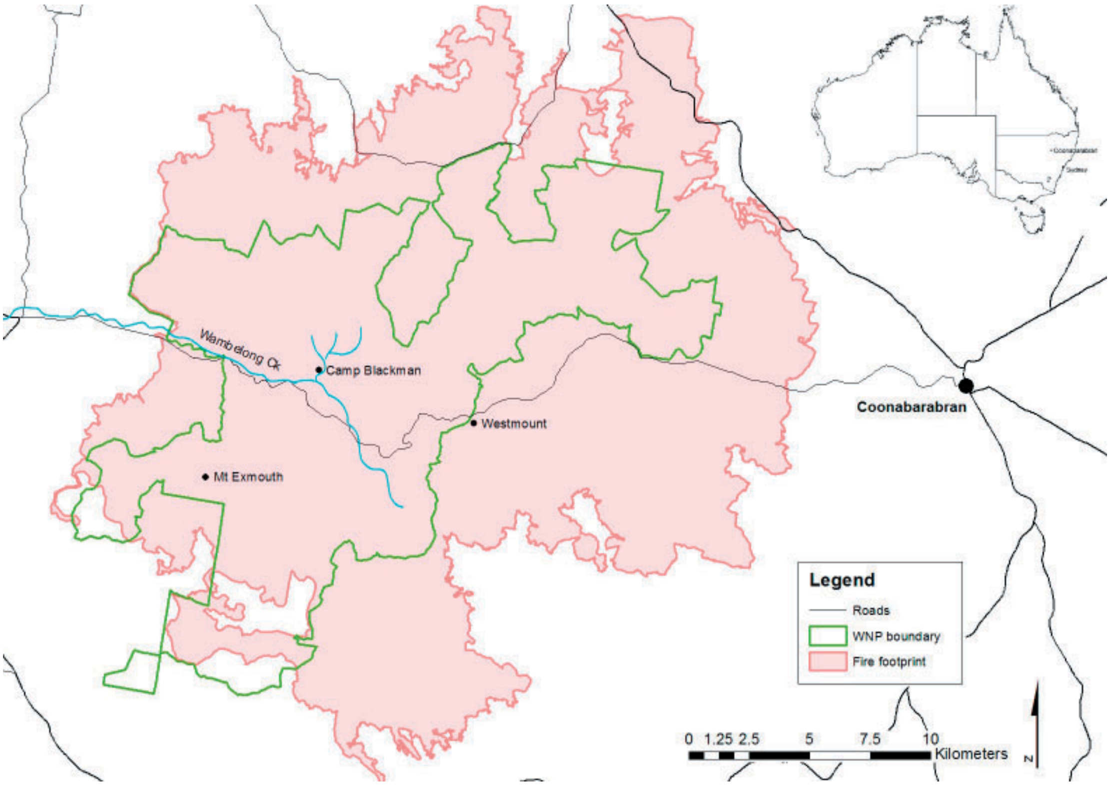

Figure 1. Study area.

The vegetation in WNP is generally open *Eucalyptus-Callitris* forest or Dry Sclerophyll Woodlands and Forests (Hunter 2008; Keith 2004), with a variable understory of shrubs and grasses.

The soils on trachytes are, in terms of the Australian Soil Classification (Isbell and NCST 2016), generally stony Brown to Red Dermosols. A typical profile on trachytes of the Warrumbungle Volcanics generally comprises: an A horizon of <20 cm dark reddish brown (5YR 3/2) fine sandy clay loam, weakly structured, with field pH 7.0; overlying a B horizon up to 60 cm of dark reddish brown (5YR 3/6) light silty clay to clay loam, moderately structured (polyhedral), with field pH 6.0. Angular gravels to stones are common throughout the profile. Soils on Pilliga Sandstone are generally Chromosols and Kurosols, with sandy Red to Yellow Kandosols also common. A typical profile on Pilliga Sandstone generally comprises: an A_1 horizon of <10 cm very dark grey (7.5YR 3/1) coarse sandy loam, with field pH 5.5; overlying an A_2 horizon of dull yellowish brown (10YR 5/3) coarse sandy clay loam with a massive earthy structure, with field pH 5.0; overlying a B_2 horizon of dull orange (7.5YR 5/4) medium clay, moderately structured, with field pH 4.5. A BC or C horizon of bright brown (7.5YR 5/6), fine light sandy clay with massive earthy structure, with field pH 4.5 may occur where bedrock is weathered. Gravels and stones are common throughout the profile. Soils profile information can be viewed on the eSPADE portal: https://www.environment.nsw.gov.au/espade2webapp/report/essentials/96542, and are described in Tulau et al. (in prep).

Data collection

Sixty-four sites were chosen around WNP in December 2015. These were selected to include the major geology/soil types, four burn severity classes mapped by Storey (2014) (0 = not burnt, 1 = low, 2 = high, 3 = extreme), and a range of topographic positions. At each site, samples were taken from 5 sub-sites in order to account for in-site variability and bulked according to the depth ranges below. Site locations were constrained by access and the routes of accessible fire trails. Each site was 10 m radius, and each was wholly contained within the one landform element (McDonald et al. 1990, National Committee on Soil and Terrain, 2009). The size of sites is less than that recommended by McKenzie et al. (2000), due to the complexity of the terrain and the need to maintain in-site consistency. At each sub-site, coarse litter was removed by hand, and finer particulate

Table 1. Sample numbers by geology/soil type and fire severity classes.

	Volcanics				Sandstones			
Depth ranges	Volc 0	Volc 1	Volc 2	Volc 3	Sandst 0	Sandst 1	Sandst 2	Sandst 3
0-5 cm	5	7	11	4	3	9	5	11
5-10 cm	3	4	7	-	1	5	2	5
10-20 cm	2	6	6	-	1	5	2	4
20-30 cm	-	2	5	-	1	3	2	4

material swept with a soft brush until predominantly mineral soil was reached, after which the cores were taken. Of the 64 sites, 27 were sampled by push core (50 mm diameter) from 0-5 cm (layer 1), 5-10 cm (layer 2), 10-20 cm (layer 3), and 20-30 cm (layer 4), or until refusal, according to Bowman et al. (2009). At the remaining 37 sites, surface samples (0-5 cm) only were collected from 5 sub-sites and bulked. Soil samples from a number of sites mapped as Warrumbungle Volcanics but determined to be coarse-grained and/or more felsic by visual inspection with a hand lens were excluded from the analyses. The resultant number of samples for each geology/soil type – fire severity class for each depth range is shown in Table 1.

Samples were tested at the Department of Planning Industry and Environment Soil and Water Environmental Laboratory at Yanco, NSW, Australia for: particle size fractions (g); vegetative matter >2 mm (g); charcoal >2 mm (g); LECO Total SOC (%); MIR spectra POC, HOC, ROC (%); LECO Total Nitrogen (%); and pH ($CalCl_2$) as per Wilson et al. (2017). Samples were dried at 40°C for 48 hours. Large plant debris, charcoal and other coarse fragments were removed and weighed. Each sample was crushed (<100 µm) and analysed by LECO for SOC and TN using high-temperature oxidative combustion (Rayment and Lyons 2011).

For the carbon fractions analysis, an 8 g aliquot of air-dried soil was split from the bulk sample and finely ground. Mid-infrared spectra were acquired from neat fine-ground samples using the Perkin-Elmer Spectrum One™ mid-Fourier-transform infrared spectroscopy (FTIR) laboratory bench spectrometer equipped with a deuterated triglycine sulfate (DTGS) detector and extended range KBr beam-splitter, scanning at 8 cm^{-1} resolution to give a spectrum range of 7800-400 cm^{-1} at a 2 cm^{-1} point spacing and with a 0.5 cm sec^{-1} scan speed. The Spectrum-One CO_2/H_2O compensation software was used for correction of atmospheric water vapour and CO_2 absorption bands. Subsamples of the powder samples were individually transferred to an auto-focusing Perkin-Elmer diffuse reflectance Fourier-transform (mid)-infrared (DRIFT) accessory sample cup holder, and scanned for 1 minute.

The development of carbon fractionation methodology and MIR calibration is described in detail by Baldock et al. (2013a,b). Samples from the national Soil Carbon Research Program (SCARP) and NSW Office of Environment and Heritage Monitoring, Evaluation and Reporting (MER) Program were used to build partial least squares regression (PLSR) models for SOC, POC, HOC and ROC. Separate calibration (for full cross validation) and validation (for an independent test set) sample sets were selected randomly from the full data set. The PLSR calibrations of SOC and fractions were carried out using the GRAMS PLSplus/IQ® software package. The spectra were mean-centred and pre-processed with GRAMS automatic baseline correction function for the optimum spectral range 4000 and 450 cm^{-1}. All carbon fraction reference data were transformed to a square root of the data before calibration, in order to minimize non-linearity in the calibration (Janik et al. 2007; Baldock et al. 2013b). The resulting cross-validation and test sample predictions were back-transformed by squaring the PLSR predicted data.

The robustness of the derived PLSR models for the SOC, POC, HOC and ROC was evaluated with 80 independent external validation samples from varying depths, soil types and land uses, that were analysed for SOC, POC, HOC and ROC by traditional methods at CSIRO Land and Water laboratories (Glen Osmond, South Australia). For 80 random validation samples, there were linear relationships between the fractions estimated using MIR spectra and the actual measurements in an approach outlined in Baldock et al. (2013a,b).

Rock and soil types were assessed in the field by hand lens as being and derived from volcanics (trachytes/mafics/felsics), sandstones, or other. In order to address site-specific resolution issues in the fire severity mapping, fire severity was determined in the field, according to a range of factors including: the abundance of woody debris on ground; the abundance of charcoal fragments and consumption of on-ground debris; evidence of tree mortality, including of *Callitris*; evidence of scorch marks on shrubs

Table 2. Digital Elevation Model (DEM)-derived parameters ranges and averages

	Elev. (m)	Slope %	Slope class	Aspect°	Aspect class	TWI	MrBVF	Contrib. area (m^2)	Profile curv.	Plan curv.	Flow dir.	Flow accum.
Min	430	1.51	1	5	1	5.41	0	1162	-0.0057	-0.2018	1	0
Max	1040	45.56	8	360	8	12.54	2.7	1439125	0.0055	0.1197	128	3428
Average	603	13.56	4	202	5	7.69	0.27	37897	0	0.0017	27	66

and shrub mortality; the abundance of pyrogenic understorey species; evidence of scorch marks on tree trunks; evidence of canopy consumption; and the type of regeneration from trees (epicormic/basal). At each site, grid references were taken, photographs taken, and geology/soil type confirmed and noted, and aspect and slope measured.

Point cloud data from a Light Detection and Ranging (LiDAR) mission flown in September 2014 was used to construct Digital Elevation Models (DEMs) at 1 to 10 m spatial resolutions. These DEMs were assessed (Shan et al. 2019) and the 5 m DEM used to derive topographic attributes including aspect, slope % and classes, profile and plan curvature, topographic wetness index (TWI) and multi-resolution valley bottom flatness (MrVBF) (Gallant et al. 2012). Other layers included the geological mapping of Troedson and Bull (2018).

Data analysis

Data were statistically analysed in R statistical software tool to determine the main factors affecting variation in the distribution of SOC, SOC fractions, N and pH. A correlation model was used to examine the overall relationships between fire severity, geology/soil classes, and a range of Digital Elevation Model (DEM)-derived parameters: aspect; elevation; slope % and class; profile and plan curvature; MrVBF; and TWI. A linear mixed-effects model (LMM) was then used to identify the key covariates. Table 2 shows the ranges and averages for each of the variables.

Data was then classified according to the key covariates and metrics of the amounts of SOC and N within each class were calculated. Spatial classes based on the key covariates were created in ArcMap 10.4 and used to spatially extrapolate site results to calculate total SOC and N within each class, and by deficit analysis, to estimate SOC and N losses over the fire ground.

Spatial extrapolation and deficit calculation

For each site, dry weight of the sample (g) was divided by the number of sub-samples (five), to obtain an average sample weight (g) per core layer. This figure was divided by the volume of the 0-5 cm section of the core (98.175 cm^3), to obtain bulk density (g/cm^3) for layer 1. For samples 27-64, an average bulk density from sites 1-36 of 1.71 g/cm^3 for trachytic soils and 1.59 g/cm^3 for sandstone-derived soils was used. Bulk density was multiplied by the proportion of total SOC in the volume standardised bulked sample to obtain the amount of total SOC in the sample (g/cm^3). Average total SOC in g/cm^3 for each fire class was converted into grams of total SOC per hectare to a depth of 5 cm (x 5 x 10^8) and to t/ha (/1 x 10^6). Data was smoothed by linear regression in order to minimise noise from incorrect fire severity classifications and low sample numbers in certain classes. The difference between the control fire class 0 and fire classes 1-3 for volcanic- and sandstone-derived soils was calculated on a per hectare basis using the mapping of Troedson and Bull (2018), and this was then multiplied by the area of each fire classes 1-3 to generate a 'deficit' C amount for each fire class as compared to the control fire class 0.

RESULTS

Model results

The correlation matrix (Figure 2) presents Pearson correlation coefficients showing the relationship between environmental variables and the subject soil properties in the topsoil (0-5 cm). Positive and negative correlations are displayed in blue and red respectively, with the correlation coefficients indicating the strength of the relationship. The matrix reveals a strong negative correlation between fire, and a slightly weaker correlation between geology/soil type, and SOC and fractions, results confirmed by the LMM.

The LMM (Supplementary Table) treats fire and geology/soil classes as independent variables, and reveals a strongly negatively correlation between total SOC, POC and HOC values and increasing fire severity, and the differential responses of geology/soil classes. For TOC Layer 1 (0-5 cm), the significant variables are geology and fire severity; for Layer 2 (5-10 cm), geology only. In the deeper subsoils of layers 3 (10-20 cm) and 4 (20-30 cm), there are no statistically significant relationships at all, possibly

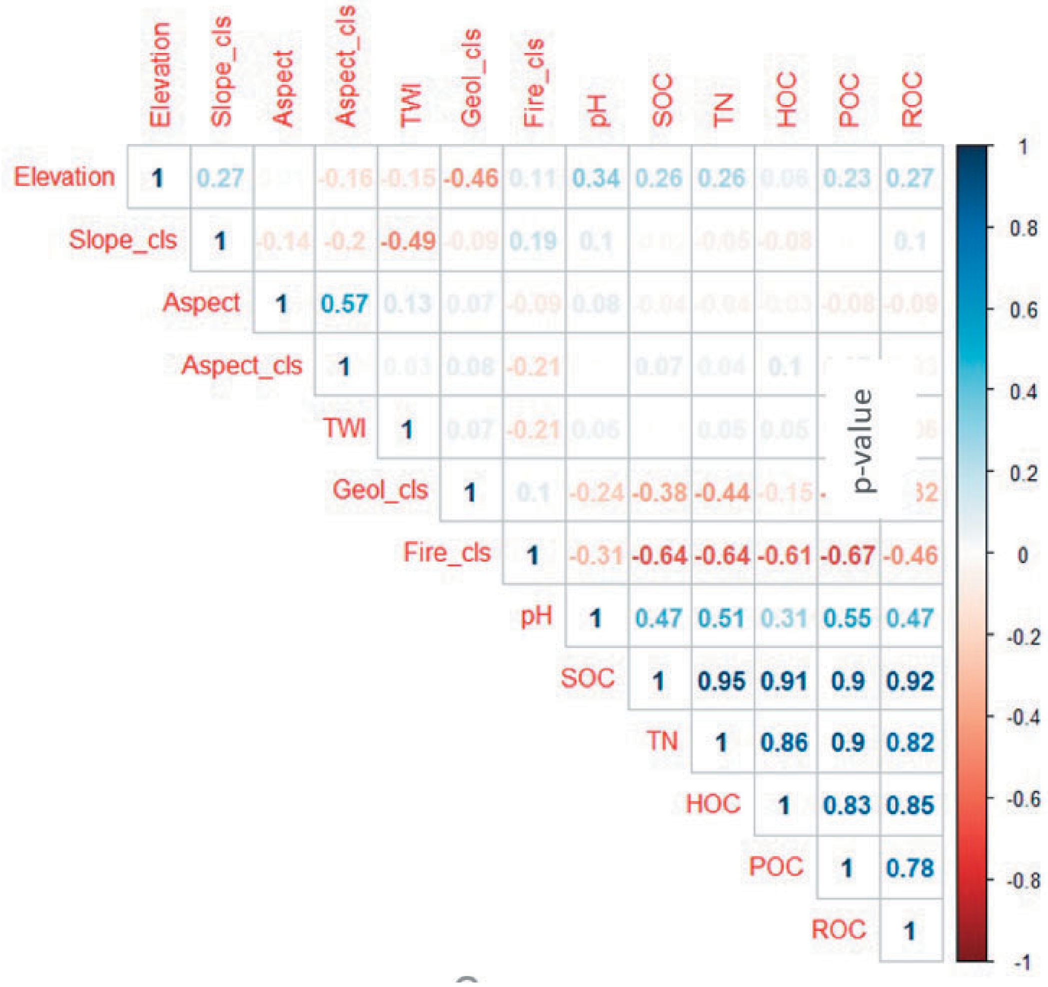

Figure 2. Topsoil Pearson correlation coefficients.

due to the generally low SOC values in that layer and that even under wildfire conditions, heat typically does not penetrate to those depths (DeBano 2000; Certini 2005). For POC Layer 1, the significant variables are geology, fire severity and flow direction; same for Layer 2; and for Layer 3, geology and slope class. For HOC Layer 1, the significant variables are geology, MrVBF and flow direction; fire severity and flow direction; same for Layer 2; and for Layer 3, geology and slope class. For ROC Layer 1, the significant variables are geology and fire severity.

The key explanatory variables are therefore fire severity and geology/soil type, and the SOC data is discussed below in consideration of those variables.

Effects of fire severity and geology/soil type on SOC

Total SOC and SOC fractions generally declined with increasing fire severity (Figure 3). Topsoil SOC in sites with low intensity burns was 14% lower than control (unburnt sites). Highly and severely burnt sites were respectively 36% and 54% lower than controls.

This fire response has been superimposed on inherent soil differences. The average total SOC of sites not burnt in 2013 was 7.45%, but the highest total SOC results were from unburnt trachytic-mafic volcanic materials, which generally had more than twice the total SOC compared to sandstone soils. The lowest total SOC value was 1.46% for a severely burnt sandstone soil on an exposed ridge.

The inherently greater percentages of SOC in trachytic-mafic volcanic soil types compared to sandier soils are likely due to the increased rates of organic matter production and lower rates of decomposition in the moister sites and soil types, compared to lower water-holding capacities and therefore lower capacity for the accumulation of SOC in the sandier materials. Volcanic materials are also generally found at higher elevations, which attract more rainfall and therefore SOC production.

POC has the lowest percentage of the SOC fractions in relation to total SOC, and HOC the highest.

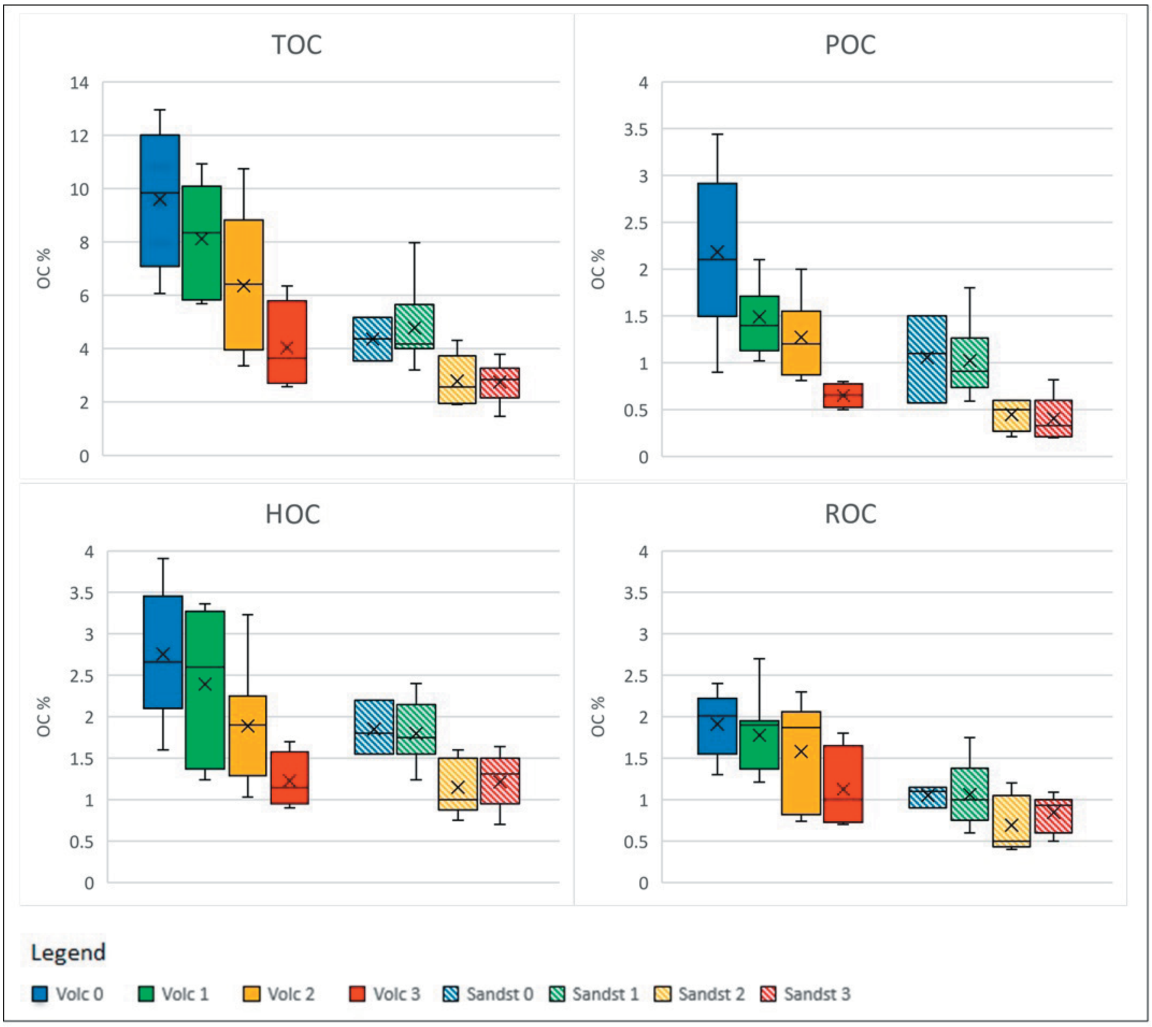

Figure 3. TOC and SOC fractions percentages in topsoils (0-5 cm), by geology/soil class and fire severity class (0 = not burnt, 1 = low severity, 2 = high severity, 3 = extreme severity).

With increasing fire severity, trachytic-mafic sites exhibited a gradual increase in the relative proportion of ROC as a percentage of total SOC. Severely burnt sandstone sites have the highest percentages of ROC, although a lack of consistency between ROC/total SOC and fire severity in the sandier soils may suggest that at least a proportion of ROC is of historic origin. POC and HOC followed similar trends in response to fire. In some low to high severity burnt sites there was an increase in topsoil total ROC, possibly due to the incorporation of burnt biomass (Gonzalez-Perez et al. 2004; Rashid 1987).

The relative decline in total SOC with increasing fire severity was greater for trachytic-mafic volcanic soils, which declined from an average of 9.60% (fire class 0) to 4.04% (fire class 3) (i.e., a reduction of 55%), whereas sandstone-derived soils total SOC values declined from 4.36% (fire class 0) to 2.74% (fire class 3) i.e. a 37% reduction).

Distribution of SOC in the soil profile

Almost half (48%) of the total SOC in unburnt control sites in WNP is located in the top 5 cm, and almost three-quarters (74%) within the top 10 cm. The average SOC in topsoils (0-5 cm) not burnt in 2013 was 7.45% (trachytes-mafics 9.60%, sandstones 4.36%). Average SOC fractions for trachytic to mafic- and sandstone-derived soils by depth are shown below (Figure 4). Averages for severely burnt volcanic geology/soil types are only available for surface materials, due to the shallow depth and rockiness of soils at these sites.

Total SOC percentages decline markedly with depth, especially in trachytic-mafic volcanic soils, underlining the concentration of SOC and nutrients in the topsoils. For example, in unburnt to low severity burnt trachytic-mafic volcanic soils, the topsoil has on average almost twice the total SOC as in layer 2. Overall, the proportion of total SOC in the topsoil as

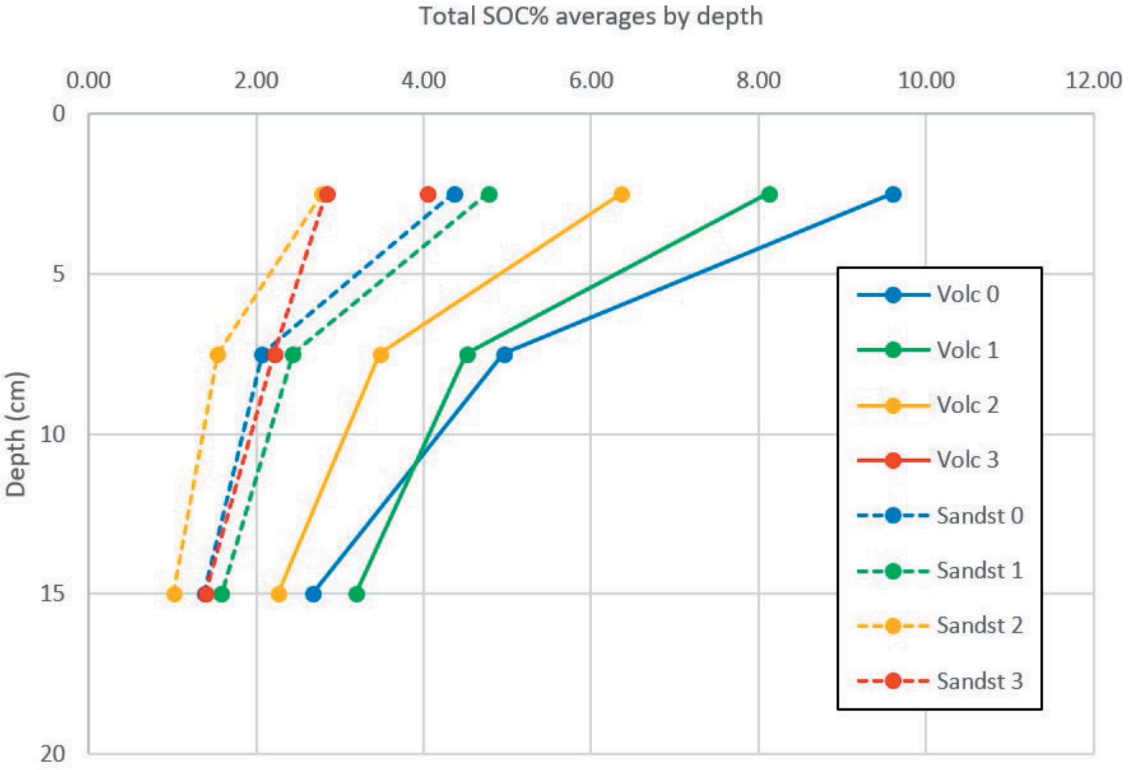

Figure 4. Total SOC % averages by geology/soil type and fire severity class

a percentage of the total profile total SOC to refusal varied from 73% to 33%.

Spatial extrapolation and calculation of total SOC losses

The total amount of SOC lost over the fire ground to a depth of 0-5 cm is estimated to be approximately 1.03 Mt (18.26 t/ha). The total amount of C lost over the fire ground from the 5-10 cm depth range is 491,457 t (8.73 t/ha). The total amount of SOC lost over the fire ground to a depth of 10 cm is therefore approximately 1.52 Mt (26.99 t/ha). These results differ from previously reported estimates (Tulau et al. 2019b), having been updated with the more accurate geological mapping of Troedson and Bull (2018) and soil mapping of Tulau et al. (in prep.). Volcanic soils amounted to 35,860 ha, or 67% of the fire ground, but this accounted for 98% of the SOC lost. Sandstone soils amounted to 17,724 ha, or 33% of the fire ground, but this accounted for only 2% of the SOC lost. This is due to the higher amounts of SOC in volcanic soils. The apparent negative deficit (increase) in low severity burnt sandstone topsoils is probably due to the incorporation of burnt vegetative matter. Relatively small apparent negative deficits in SOC for sandstone subsoils are likely errors caused by the low number of unburnt sandstone samples and/or fire severity misclassifications.

Figure 5 shows the areas of WNP and the fire ground that correspond to the geology and fire severity classes in Table 3, using the fire severity mapping of Storey (2014) and the geological mapping of Troedson and Bull (2018). Areas of burnt cleared land are included in low fire severity classes. Geological mapping is generalised to display Warrumbungle Volcanics and predominantly sandstone units, which include small areas of alluvium and other materials.

DISCUSSION AND CONCLUSIONS

In WNP, almost half (48%) of the SOC in unburnt control sites is in the top 5 cm, and almost three-quarters (74%) within the top 10 cm, underlining the concentration of SOC and nutrients in the topsoils, and their susceptibility to wildfire.

The statistical models demonstrated that the key covariates related to total SOC, SOC fractions and N were fire severity and the geology/soil type. Sandier and especially sandstone-derived soils have less SOC irrespective of the fire severity class, probably due to the sandier nature of those materials (Tulau et al. in prep), and therefore lower water-holding capacity and capacity for the accumulation of SOC, but most SOC

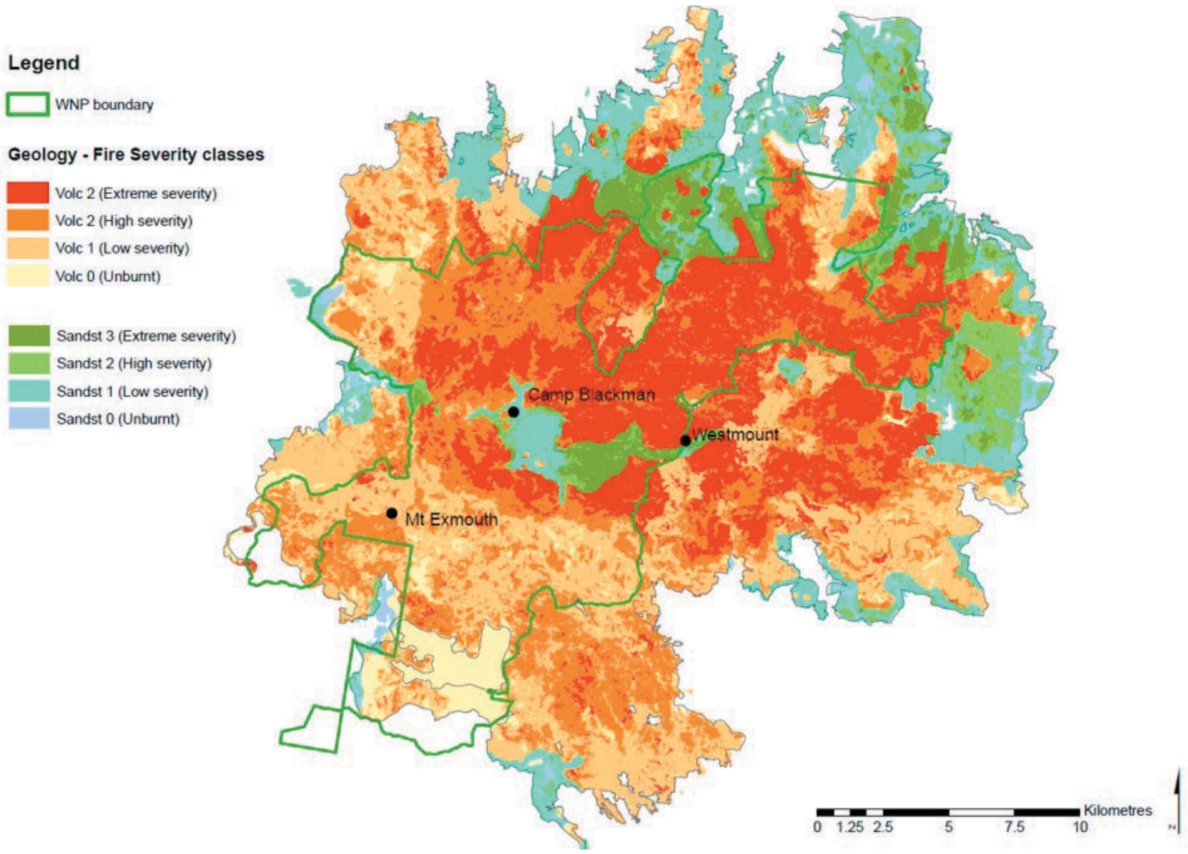

Figure 5. Areas of geology-fire severity classes

Table 3. Carbon deficit and loss calculations

Geology and Fire Class	Area (ha)	Deficit to Fire Class 0 (control) for 0-5 cm (in tonnes)	Deficit to Fire Class 0 (control) for 5-10 cm (in tonnes)	Total SOC loss (in tonnes)
Volcanic 0	7104	0	0	Volcanic = -1,752,204 Sandstone = -36,689 Overall = -1,788,893
Sandstone 0	5033	0	0	
Volcanic 1	6554	-230,239	-195,015	
Sandstone 1	2013	4,481	24,397	
Volcanic 2	12,225	-338,389	-255,456	
Sandstone 2	5198	-49,257	7,507	
Volcanic 3	9977	-524,624	-208,481	
Sandstone 3	5480	-45,956	22,139	
Totals		-1,183,984	-604,909	

fractions in all soil types were strongly negatively correlated with increasing fire severity.

Topsoil SOC in sites with low intensity burns was 14% lower than control (unburnt sites). High and extreme severity burnt sites were 36% and 54% lower than controls. As a result of the fire, there was an average loss of SOC in the top 5 cm of more than 60 % in severely burnt sites, and a 57% loss in the top 10 cm, which is consistent with figures reported elsewhere (Kutiel and Naveh 1987; Fernández et al. 1997; Baird et al 1999; Neary et al. 1999; Neary and Overby 2006).

The lowest total SOC values were from severely burnt sandstone ridges, but the relative decline in total SOC with increasing fire severity was greater for trachytic-mafic volcanic soils, because of the higher total SOC values.

Importantly, total SOC and N percentages declined in a near-linear manner with increasing fire severity, with no thresholds apparent. This is because the amount of SOC consumed and volatilised in fire is related to increased soil temperature, and therefore to fire intensity and severity (Campbell et al. 1977; Giovannini and Lucchesi 1997; Hille and den Ouden, 2005; Homann et al. 2011), but even low severity fire can potentially have significant impacts on SOM and SOC due to the low temperature of volatilisation of carbon (Tiedemann 1987; Prentice et al. 2001).

The highest SOC values identified were from trachytic-mafic volcanic topsoils that were not burnt (fire class 0) (mean value 9.6%). This is much higher than averages found generally in the central west of NSW – an analysis of NSW Soil and Land Information System (SALIS) data shows that the mean topsoil total SOC values in cropping and pasture systems is 1.7%, thus underlining the importance of forested ecosystems including national parks in carbon soil sequestration, and of WNP with its high proportion of trachytic and clay soils in particular.

Total SOC can reach >10% in the absence of fire. Unfortunately, due to a lack of long-unburnt sites, it is difficult to determine the long-term SOC recovery trajectory. In short to medium terms, the recovery trajectory appears to be highly dependent on rainfall amounts and intensity.

Losses in SOM can affect the catchment hydrology by reducing the amount of water that may be stored in topsoils, therefore increasing runoff-infiltration ratios and affecting geomorphic responses of drainage lines, primarily by drainage line incision. It is likely that the loss of 2.61 Mt of SOM over the fire ground has resulted in increased runoff-infiltration ratios, and this has shifted drainage lines in areas subject to high fire severity into a new erosive trajectory marked by periodic sedimentation (Tulau et al. 2019b).

Soil sampling sites were plotted on ArcMap with mapping of previous fires of known dates in an attempt to estimate the likely long-term post-burn recovery trajectory of SOC. Unfortunately, most sites not burnt in 2013 were affected by the extensive 1967 Exmouth fire, as a result of which there are very few data points beyond 48 years old. It is therefore difficult to determine the SOC recovery trajectory beyond several decades. However, notwithstanding the recovery of vegetation and groundcover, the impacts of the 2013 fire on SOC and rates of recovery from elsewhere in south-eastern Australia (Bowd et al. 2019) suggest that it is likely the recovery of SOC to near pre-burn levels and the restoration of catchment and creek condition to near pre-fire hydrologic responses is expected to take several decades in the absence of fire.

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Supplementary Table. Linear mixed-effects model fit by Restricted Maximum Likelihood.

Geol 2 = felsic volcanics; Geol 3 = sandstones; Fire 1 = low severity; Fire 2 = high severity; Fire 3 = extreme severity; MrVBF = multi-resolution valley bottom flatness; TWI = topographic wetness index.

TOC

Layer 1

	Value	Std error	t-value	p-value
(Intercept)	12.256161	3.08652	3.970865	0.0002
Geol_2	-2.664849	0.78752	-3.383837	0.0015
Geol 3	-3.121796	0.65448	-4.769894	0.0000
Fire 1	-1.012139	0.75661	-1.337733	0.1874
Fire 2	-3.311219	0.78299	-4.228932	0.0001
Fire 3	-3.698027	0.69466	-5.323529	0.0000
Aspect	-0.003319	0.00241	-1.377493	0.1749
Elevation	0.000563	0.00274	0.205353	0.8382
Slope %	0.067930	0.06199	1.095765	0.2788
Slope class	-0.853544	0.59450	-1.435741	0.1577
Profile curvature	20.365870	118.71345	0.171555	0.8645
Plan curvature	-3.062188	8.38916	-0.365017	0.7167
MrVBF	-0.969888	0.60044	-1.615305	0.1129
Flow direction	-0.014126	0.00710	-1.990888	0.0523
Flow accumulation	0.000188	0.00070	0.267370	0.7904
TWI	0.012176	0.25055	0.048598	0.9614

Layer 2

	Value	Std error	t-value	p-value
(Intercept)	0.43144	4.21014	0.1024774	0.9201
Geol 3	-2.04991	0.85702	-2.3919030	0.0340
Fire 1	0.23849	1.11483	0.2139253	0.8342
Fire 2	-2.03489	1.27187	-1.5999218	0.1356
Fire 3	-0.52381	1.13928	-0.4597781	0.6539
Aspect	0.00389	0.00323	1.2048245	0.2515
Elevation	0.00229	0.00439	0.5213960	0.6116
Slope %	-0.11383	0.09108	-1.2498438	0.2352
Slope class	1.02434	0.86672	1.1818634	0.2602
Profile curvature	-93.32452	188.18792	-0.4959113	0.6289
Plan curvature	-2.94721	14.01432	-0.2102996	0.8370
MrVBF	-1.21117	1.09300	-1.1081162	0.2895
Flow direction	-0.00860	0.01252	-0.6864945	0.5055
Flow accumulation	-0.00018	0.00081	-0.2164595	0.8323
TWI	0.05274	0.35889	0.1469593	0.8856

Layer 3

	Value	Std error	t-value	p-value
(Intercept)	-1.34931	4.15097	-0.3250582	0.7526
Geol 3	-1.16796	0.77500	-1.5070417	0.1661
Fire 1	1.20262	1.09151	1.1017941	0.2991
Fire 2	-0.40958	1.18585	-0.3453901	0.7377
Fire 3	0.02243	1.13920	0.0196851	0.9847
Aspect	0.00534	0.00320	1.6705571	0.1291
Elevation	0.00199	0.00375	0.5322056	0.6075
Slope %	-0.10229	0.08458	-1.2093443	0.2573
Slope class	0.89901	0.79756	1.1272027	0.2888
Profile curvature	-122.07682	167.35477	-0.7294493	0.4843
Plan curvature	9.47878	12.84827	0.7377475	0.4795
MrVBF	-0.79661	0.93359	-0.8532800	0.4156
Flow direction	0.00021	0.01080	0.0196655	0.9847
Flow accumulation	0.00024	0.00071	0.3370680	0.7438
TWI	-0.08933	0.32145	-0.2778817	0.7874

Layer 4

	Value	Std error	t-value	p-value
(Intercept)	0.86519	12.28068	0.0704513	0.9502
Geol 3	-0.33788	1.12572	-0.3001478	0.7924
Fire 1	1.51200	13.75150	0.1099515	0.9225
Fire 2	0.52657	14.73110	0.0357451	0.9747
Fire 3	0.70777	16.57277	0.0427067	0.9698
Aspect	0.00492	0.00445	1.1047179	0.3844
Elevation	0.00226	0.00524	0.4310796	0.7084
Slope %	-0.06599	0.16873	-0.3910655	0.7335
Slope class	0.26115	1.17249	0.2227296	0.8444
Profile curvature	-35.71017	298.52880	-0.1196205	0.9157
Plan curvature	-9.58956	80.66136	-0.1188866	0.9162
MrVBF	-1.06857	4.28692	-0.2492641	0.8264
Flow direction	-0.00402	0.04295	-0.0936238	0.9339
Flow accumulation	0.02063	0.17441	0.1182934	0.9166
TWI	-0.35858	0.57175	-0.6271666	0.5946

POC

Layer 1

	Value	Std error	t-value	p-value
(Intercept)	2.666753	0.725258	3.676971	0.0006
Geol_2	-0.489475	0.185049	-2.645114	0.0111
Geol 3	-0.811140	0.153787	-5.274449	0.0000
Fire 1	-0.276878	0.177785	-1.557377	0.1261
Fire 2	-0.697840	0.183984	-3.792933	0.0004

Fire 3	-0.938130	0.163228	-5.747370	0.0000
Aspect	-0.000288	0.000566	-0.509310	0.6129
Elevation	-0.000726	0.000645	-1.126824	0.2655
Slope %	0.010749	0.014567	0.737914	0.4642
Slope class	-0.136131	0.139693	-0.974505	0.3348
Profile curvature	30.993492	27.894792	1.111085	0.2722
Plan curvature	-0.214624	1.971251	-0.108877	0.9138
MrVBF	-0.275801	0.141088	-1.954817	0.0566
Flow direction	-0.004050	0.001667	-2.429386	0.0190
Flow accumulation	-0.000174	0.000165	-1.054436	0.2971
TWI	0.050532	0.058872	0.858326	0.3951

Layer 2

	Value	Std error	t-value	p-value
(Intercept)	2.666753	0.725258	3.676971	0.0006
Geol_2	-0.489475	0.185049	-2.645114	0.0111
Geol 3	-0.811140	0.153787	-5.274449	0.0000
Fire 1	-0.276878	0.177785	-1.557377	0.1261
Fire 2	-0.697840	0.183984	-3.792933	0.0004
Fire 3	-0.938130	0.163228	-5.747370	0.0000
Aspect	-0.000288	0.000566	-0.509310	0.6129
Elevation	-0.000726	0.000645	-1.126824	0.2655
Slope %	0.010749	0.014567	.737914	0.4642
Slope class	-0.136131	0.139693	-0.974505	0.3348
Profile curvature	30.993492	27.894792	1.111085	0.2722
Plan curvature	-0.214624	1.971251	-0.108877	0.9138
MrVBF	-0.275801	0.141088	-1.954817	0.0566
Flow direction	-0.004050	0.001667	-2.429386	0.0190
Flow accumulation	-0.000174	0.000165	-1.054436	0.2971
TWI	0.050532	0.058872	0.858326	0.3951

Layer 3

	Value	Std error	t-value	p-value
(Intercept)	-0.072269	0.578176	-0.124994	0.9033
Geol 3	-0.364138	0.107948	-3.373278	0.0082
Fire 1	0.135002	0.152033	0.887973	0.3977
Fire 2	0.053508	0.165174	0.323949	0.7534
Fire 3	-0.054015	0.158676	-0.340407	0.7414
Aspect	0.000835	0.000445	1.874002	0.0937
Elevation	-0.000255	0.000522	-0.488198	0.6371
Slope %	-0.023740	0.011781	-2.015069	0.0747
Slope class	0.297482	0.111090	2.677850	0.0253
Profile curvature	9.968292	23.310327	0.427634	0.6790
Plan curvature	2.442304	1.789596	1.364723	0.2055
MrVBF	0.037734	0.130036	0.290184	0.7783

Flow direction	0.001672	0.001504	1.111358	0.2952
Flow accumulation	0.000119	0.000099	1.203121	0.2596
TWI	-0.057094	0.044774	-1.275158	0.2342

Layer 4

	Value	Std error	t-value	p-value
(Intercept)	1.250031	1.64261	0.7610023	0.5261
Geol 3	-0.395471	0.15057	-2.6264562	0.1195
Fire 1	-0.782161	1.83934	-0.4252392	0.7120
Fire 2	-0.971479	1.97037	-0.4930436	0.6708
Fire 3	-1.203194	2.21670	-0.5427852	0.6417
Aspect	0.001095	0.00060	1.8387238	0.2073
Elevation	-0.000172	0.00070	-0.2449842	0.8293
Slope %	-0.007376	0.02257	-0.3268196	0.7748
Slope class	0.244759	0.15683	1.5606861	0.2590
Profile curvature	6.651539	39.92996	0.1665801	0.8830
Plan curvature	4.907740	10.78893	0.4548868	0.6938
MrVBF	0.197848	0.57340	0.3450429	0.7630
Flow direction	-0.002997	0.00574	-0.5216203	0.6539
Flow accumulation	-0.007725	0.02333	-0.3311284	0.7720
TWI	-0.115026	0.07647	-1.5041038	0.2715

HOC

Layer 1

	Value	Std error	t-value	p-value
(Intercept)	3.238920	1.02933	3.146645	0.0029
Geol_2	-0.840827	0.26263	-3.201551	0.0025
Geol 3	-0.675415	0.21826	-3.094511	0.0033
Fire 1	-0.283232	0.25232	-1.122504	0.2673
Fire 2	-0.946867	0.26112	-3.626173	0.0007
Fire 3	-0.956897	0.23166	-4.130587	0.0001
Aspect	-0.000615	0.00080	-0.765067	0.4481
Elevation	-0.000076	0.00091	-0.083406	0.9339
Slope %	0.012221	0.02067	0.591141	0.5573
Slope class	-0.196705	0.19826	-0.992164	0.3262
Profile curvature	23.305759	39.58978	0.588681	0.5589
Plan curvature	-3.162300	2.79770	-1.130319	0.2641
MrVBF	-0.442211	0.20024	-2.208410	0.0321
Flow direction	-0.006357	0.00237	-2.686709	0.0099
Flow accumulation	0.000115	0.00023	0.492166	0.6249
TWI	0.070200	0.08355	0.840171	0.4051

Layer 2

	Value	Std error	t-value	p-value
(Intercept)	1.00016	1.93273	0.5174880	0.6142
Geol 3	-0.59719	0.39343	-1.5179228	0.1549
Fire 1	-0.14586	0.51178	-0.2850089	0.7805
Fire 2	-0.97688	0.58387	-1.6731089	0.1202
Fire 3	-0.22850	0.52300	-0.4369048	0.6699
Aspect	0.00067	0.00148	0.4509416	0.6601
Elevation	0.00066	0.00202	0.3272662	0.7491
Slope %	-0.04495	0.04181	-1.0752237	0.3034
Slope class	0.32262	0.39788	0.8108396	0.4332
Profile curvature	-35.07828	86.39059	-0.4060428	0.6919
Plan curvature	-6.87613	6.43349	-1.0688014	0.3062
MrVBF	-0.69847	0.50176	-1.3920451	0.1892
Flow direction	-0.00444	0.00575	-0.7718212	0.4552
Flow accumulation	0.00006	0.00037	0.1586309	0.8766
TWI	0.01135	0.16475	0.0689148	0.9462

Layer 3

	Value	Std error	t-value	p-value
(Intercept)	-0.04692	1.81038	-0.0259165	0.9799
Geol 3	-0.44778	0.33801	-1.3247836	0.2179
Fire 1	0.31174	0.47605	0.6548438	0.5289
Fire 2	-0.27334	0.51719	-0.5285002	0.6099
Fire 3	0.04094	0.49685	0.0824007	0.9361
Aspect	0.00184	0.00139	1.3155839	0.2208
Elevation	0.00031	0.00163	0.1872141	0.8556
Slope %	-0.05882	0.03689	-1.5945211	0.1453
Slope class	0.48314	0.34784	1.3889650	0.1982
Profile curvature	-53.03660	72.98915	-0.7266368	0.4859
Plan curvature	0.12863	5.60357	0.0229557	0.9822
MrVBF	-0.49051	0.40717	-1.2046914	0.2590
Flow direction	0.00033	0.00471	0.0704299	0.9454
Flow accumulation	0.00023	0.00031	0.7358690	0.4805
TWI	-0.05945	0.14020	-0.4240717	0.6815

Layer 4

	Value	Std error	t-value	p-value
(Intercept)	1.22411	5.89657	0.2075974	0.8548
Geol 3	-0.18842	0.54052	-0.3485974	0.7607
Fire 1	-0.27887	6.60279	-0.0422350	0.9701
Fire 2	-0.73486	7.07315	-0.1038944	0.9267
Fire 3	-0.56269	7.95742	-0.0707124	0.9501
Aspect	0.00244	0.00214	1.1418439	0.3718

Elevation	0.00090	0.00252	0.3588493	0.7540
Slope %	-0.04479	0.08102	-0.5528379	0.6359
Slope class	0.26081	0.56297	0.4632803	0.6887
Profile curvature	-51.02924	143.33876	-0.3560045	0.7559
Plan curvature	-2.31740	38.72960	-0.0598354	0.9577
MrVBF	-0.45801	2.05837	-0.2225114	0.8446
Flow direction	-0.00380	0.02062	-0.1841867	0.8709
Flow accumulation	-0.00449	0.08374	-0.0536468	0.9621
TWI	-0.17784	0.27453	-0.6478159	0.5835

ROC

Layer 1

	Value	Std error	t-value	p-value
(Intercept)	2.459716	0.785380	3.131879	0.0030
Geol_2	-0.519738	0.200389	-2.593645	0.0126
Geol 3	-0.642682	0.166535	-3.859135	0.0003
Fire 1	-0.220615	0.192522	-1.145919	0.2576
Fire 2	-0.570361	0.199236	-2.862741	0.0063
Fire 3	-0.603572	0.176759	-3.414661	0.0013
Aspect	-0.000760	0.000613	-1.238872	0.2215
Elevation	0.000057	0.000698	0.081947	0.9350
Slope %	0.019541	0.015775	1.238753	0.2216
Slope class	-0.163963	0.151273	-1.083892	0.2839
Profile curvature	9.728189	30.207210	0.322049	0.7488
Plan curvature	-0.731408	2.134663	-0.342634	0.7334
MrVBF	-0.176535	0.152784	-1.155452	0.2537
Flow direction	-0.002626	0.001805	-1.454542	0.1524
Flow accumulation	0.000038	0.000179	0.214833	0.8308
TWI	0.013312	0.063753	0.208806	0.8355

Layer 2

	Value	Std error	t-value	p-value
(Intercept)	-0.566301	1.18074	-0.4796137	0.6401
Geol 3	-0.353667	0.24035	-1.4714472	0.1669
Fire 1	0.139021	0.31266	0.4446432	0.6645
Fire 2	-0.376336	0.35670	-1.0550513	0.3122
Fire 3	-0.046983	0.31951	-0.1470452	0.8855
Aspect	0.001090	0.00091	1.2026915	0.2523
Elevation	0.000384	0.00123	0.3121280	0.7603
Slope %	-0.030735	0.02554	-1.2032938	0.2521
Slope class	0.348975	0.24307	1.4356798	0.1766
Profile curvature	-22.770250	52.77781	-0.4314360	0.6738
Plan curvature	1.395930	3.93036	0.3551664	0.7286
MrVBF	-0.235937	0.30654	-0.7696907	0.4564

Flow direction	0.000139	0.00351	0.0396516	0.9690
Flow accumulation	-0.000007	0.00023	-0.0293908	0.9770
TWI	0.029595	0.10065	0.2940385	0.7738

Layer 3

	Value	Std error	t-value	p-value
(Intercept)	-0.30866	1.08423	-0.2846814	0.7823
Geol 3	-0.15477	0.20243	-0.7645520	0.4641
Fire 1	0.22918	0.28510	0.8038585	0.4422
Fire 2	-0.21128	0.30974	-0.6821243	0.5123
Fire 3	-0.17899	0.29756	-0.6015227	0.5623
Aspect	0.00169	0.00084	2.0268848	0.0733
Elevation	0.00051	0.00098	0.5234739	0.6133
Slope %	-0.03248	0.02209	-1.4702340	0.1756
Slope class	0.30003	0.20832	1.4402275	0.1837
Profile curvature	-31.68075	43.71296	-0.7247450	0.4870
Plan curvature	2.45959	3.35596	0.7329019	0.4823
MrVBF	-0.17033	0.24385	-0.6984824	0.5025
Flow direction	0.00117	0.00282	0.4154904	0.6875
Flow accumulation	0.00013	0.00019	0.7176366	0.4912
TWI	-0.06842	0.08396	-0.8148629	0.4362

Layer 4

	Value	Std error	t-value	p-value
(Intercept)	1.260012	3.64993	0.3452155	0.7629
Geol 3	-0.101889	0.33458	-0.3045308	0.7895
Fire 1	-0.345996	4.08707	-0.0846561	0.9402
Fire 2	-0.590967	4.37822	-0.1349788	0.9050
Fire 3	-0.732187	4.92558	-0.1486499	0.8955
Aspect	0.001143	0.00132	0.8639600	0.4787
Elevation	0.000492	0.00156	0.3155929	0.7822
Slope %	-0.003699	0.05015	-0.0737639	0.9479
Slope class	0.086050	0.34848	0.2469340	0.8280
Profile curvature	-16.394853	88.72550	-0.1847817	0.8704
Plan curvature	3.177072	23.97330	0.1325255	0.9067
MrVBF	0.080879	1.27411	0.0634789	0.9552
Flow direction	-0.002075	0.01277	-0.1625314	0.8858
Flow accumulation	0.000053	0.05184	0.0010137	0.9993
TWI	-0.169418	0.16993	-0.9969915	0.4238