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Sediment aggregation and water quality in wildfire-affected river basins

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Abstract. Off-site transfer of nutrient-rich burnt soil has implications for downstream water quality. Coarsening of effective particle size (EPS) distributions in burnt material via aggregation of fines into composite particles modifies post-fire sediment and nutrient transport dynamics. Experiments were undertaken to establish temperature controls on wildfire-enhanced soil aggregation. Burnt and unburnt soil from a temperate eucalypt forest were analysed for EPS and settling velocity using a LISST-ST (Laser *In Situ* Scatter and Transmissometry with Settling Tube) particle size analyser. Next, samples were burnt (250–550°C) before further analysis with the LISST-ST. Settling velocities of naturally burnt soil aggregates were greater than unburnt aggregates of the same EPS. Experimental burning indicated that dense water-stable aggregates form at relatively low temperatures (250°C) probably due to distillation and carbonisation, through pyrolysis, of organic volatiles in surface litter. Under these conditions, the EPS distribution of burnt surface soil coarsens with up to 50% of the <63-μm fraction becoming aggregated. A positive relationship between 'plant-available' phosphorus and burn temperature was observed. Given that a large proportion of soil particulate phosphorus is associated with the <63-μm fraction, fire-related aggregation processes have potentially important implications for post-fire fine sediment and nutrient transport and storage dynamics.

Additional keywords: phosphorus, soil aggregate.

Introduction

Wildfire and downstream water quality

Landscape disturbance by wildfire renders hillslope soils susceptible to erosion by water. Erosion rates and sediment yields of up to three orders of magnitude greater than unburnt reference sites have been reported (Shakesby and Doerr 2006). The widespread loss of topsoil from burnt forest landscapes presents important on-site management issues with respect to soil and forest health and recovery. In the context of climate change and increasing pressure on water resources in fire-prone areas, the off-site downstream impacts of wildfire on aquatic habitat and water quality are rising up management agendas. In addition to the many problems associated with elevated fine sediment inputs to streams and rivers, post-fire nutrient fluxes and impacts on water quality are receiving greater attention (Rannalli 2004) because, in addition to soil material, wildfires mobilise substantial quantities of highly available nutrients to lakes and streams (Spencer *et al*. 2003).

Forest ecosystems in fire-prone areas of the world are generally quite resilient to wildfire effects. For example, Mediterranean ecosystems have shown quick recovery (<5 years), in terms of return to pre-disturbance states of vegetation cover, and hence of soil erosion rates (Wittenberg *et al*. 2007), although recovery times in terms of catchment sediment yield can be longer (Mayor *et al*. 2007). Wilkinson *et al*. (2007) observed enhanced sediment and nutrient levels within receiving stream and river channel networks to decline during a 5-year post-fire period. In many systems, fire-related disturbances can be important for ecosystem development. For example, Burton (2005) reports that although immediate local impacts on stream habitat can be severe, post-fire floods can lead to rejuvenation of stream habitats. Flushing of accumulated channel-stored fine sediment by post-fire floods and the associated import of gravel, woody debris and nutrients can actually improve habitat diversity and hence lead to higher fish productivity 5–10 years after the fire. From a water quality perspective, however, short-term downstream impacts linked to post-fire sediment and nutrient flushes from hillslope to reservoir remain a significant problem. Blake *et al*. (2009) reported post-fire particulate phosphorus yields from burnt pristine forest in a water supply reservoir catchment, that subsequently experienced major algal blooms, to be equivalent to those from agricultural land. In the context of future climate change scenarios, the increased risk of wildfire (McCarthy *et al*. 2001) and increased pressure on water resources (Ice *et al*. 2004) demand an improved predictive capacity for post-fire water quality incidents.

Fire-induced sediment aggregation

Recent work in unburnt river basins illustrates the importance of considering the composite nature of sediment particles from

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erosion through to channel transport and deposition (Droppo 2001; Droppo *et al.* 2005), in the construction of sediment budgets. Against this background, wildfire has been shown to have a profound effect on soil aggregate structure and stability in some burnt river basins where, instead of the more commonly observed decrease in aggregate stability, aggregates are observed to be more robust after fire (Dyrness and Youngberg 1957; Ulery and Graham 1993; Giovannini and Lucchesi 1997; Garcia-Corona *et al.* 2004) with various mechanisms identified for increased aggregate robustness (e.g. alteration of iron and formation of aluminosilicates during burning, which cement existing aggregates). The degree of aggregation can differ with soil depth and depends on the balance between geochemical and biochemical changes in the mineral and organic components, all of which will be dependent on soil temperature attained.

Blake *et al.* (2007) extended study of the impact of wildfire on the effective particle size of burnt and unburnt soil to include the fluvial behaviour of modified soil aggregates. Individual aggregate settling behaviour was quantified using the microscopic methods described by Droppo (2001). Burnt soil aggregates exhibited significantly higher settling velocities than unburnt particles of similar diameter, reflecting an increase in density linked to reductions in organic content and pore space where changes in settling behaviour are likely to modify post-fire sediment transport dynamics. Given the affinity of trace elements for fine-grained soil particles (Stone and Mudroch 1989; Stone and English 1993; Owens and Walling 2002), modification of the transport dynamics of fine sediment (i.e. clay and silt grains transported as sand-size particles) will also modify the transport dynamics of particle-associated phosphorus in burnt systems with an increased potential for phosphorus storage in channel bed sediment linked to the increased settling velocity of fire-modified aggregates.

The primary aim of this study was to determine, via laboratory experimentation, the temperature thresholds under which the effective particle size distributions of fire-prone eucalypt forest soil, and hence settling velocity of water-stable aggregates, are modified by fire. The hypothesis that wildfire increases the potential bio-availability of phosphorus in burnt fluvial sediment was also tested to evaluate the implications of channel storage of burnt aggregated sediment for water quality.

Experimental design

Field sampling

Materials for laboratory experimentation were collected from an area of eucalypt forest within the Thirlemere Lakes National Park, New South Wales, Australia (34°13′37.85″S, 150°32′16.01″E) that experienced a range of burn severities during a wildfire event in January 2007. Samples of severely burnt (defined by extensive canopy loss, see Chafer *et al.* 2004) surface soil were gently recovered from 0.5-m^2 plots. Unburnt reference materials were collected from long-unburnt forest some 200 m from the burnt area where the presence of *Pittosporum undulatum* trees, which are sensitive to fire, was used to indicate a prolonged fire-free period at this site. In addition, samples of unburnt subsurface material were collected from recently constructed ant mounds within the unburnt zone.

Experimental burning of soil material

To simulate the impact of wildfire on soil aggregation, separate subsamples of all three soils (burnt surface, unburnt surface and unburnt subsurface) were subjected to temperatures of 550, 350 and 250°C for 20 min in a pre-heated muffle furnace where temperatures reflect the approximate thresholds for combustion of organic matter and combustion and volatilisation of water repellent compounds in these soils. Eucalypt leaf litter was included in unburnt surface materials. All samples were air-cooled and then gently sieved to 250 μm for analysis of effective particle size and settling velocity. Particles greater than 250 μm were excluded to minimise the influence of operator error on measurement of settling velocity, as described below.

Effective particle size and settling velocity

Effective particle size and settling velocity were determined using a Sequoia Scientific, Inc. (Bellevue, WA, USA) laser *in situ* scatter and transmissometry with settling tube (LISST-ST) particle size analyser setup in a controlled-temperature room at 20°C. The LISST-ST has a working particle size range of 2–500 μm and can be used to measure instantaneous particle size distributions, by laser diffraction, and also to estimate the settling velocity of eight key particle size classes (360, 186, 96, 49, 25, 13, 7 and 3 μm). The apparatus (Fig. 1) comprises a 250-mL volume measurement chamber through which the laser beam is passed to quantify the effective particle size distribution of the material in suspension. To assess particle settling velocity, the sample was introduced into the top of the settling column, which was secured above the measurement chamber (Williams 2005) and filled with water (at 20°C). Approximately 0.5 g of each sample was wetted in a Petri dish. The LISST-ST instrument was then set to take a series of particle size distribution measurements over a 48-min period, and the sample introduced to the water column to coincide with the first measurement ($t = 0$).

As the experiment progressed, the sample settled though the water column and the largest particle size classes progressively disappeared from the measured distribution as they settled beyond the depth of the measurement cell. In this way, the instrument software was able to assign a settling velocity to specific size classes from the beginning of the experiment to the time at which that particular size class no longer featured in the measured distribution. This method provides information on the bulk behaviour of the sample, as opposed to discrete particles (cf. Blake *et al.* 2007), and is therefore arguably more representative of bulk sediment behaviour. However, it should also be noted that the measurement provided relates to the slowest particles of any particular size class and hence sand grains (discrete particles of the same size as the aggregates of interest) are prone to operational exclusion. The settling experiment was repeated five times for each sample.

The overall effective particle size of each sample was determined using the LISST instrument without the settling tube. Approximately 0.5 g of each sample was turned end over end for 30 s in a polypropylene bottle before being introduced to the measurement cell. Particle size distributions reported are the mean of five repeat runs where each run represents the mean of five consecutive measurements of the same subsample.

Fig. 1. Photograph of the laser *in situ* scatter and transmissometry with settling tube apparatus setup for measurement of particle settling velocity in the laboratory.

Total and 'plant-available' phosphorus

To quantify the total phosphorus content of each experimentally burnt soil, the <250-μm subsamples were digested under reflux in a mixture of concentrated nitric and sulfuric acids (with antimony potassium tartrate as a catalyst) and then analysed by continuous air-segmented flow colourimetry using a GmbH AutoAnalyser 3 (AA3; Bran & Luebbe, Norderstedt, Germany) visible spectrophotometry system. 'Plant-available' phosphorus was estimated using Bray's reagent (0.3 M NH_4F and 0.025 M HCl at a solution to soil ratio of 7 : 1) and the extractant analysed as above (see Neyroud and Lischer (2003) for discussion of 'plant-available' phosphorus determination).

Data analysis

A two-way ANOVA test of particle size class (360, 185, 95, 49 and 25 μm) by original burn severity (unburnt surface, burnt surface and unburnt subsurface/ant mound) was performed on the settling velocity data from each group of experimentally burnt samples (550, 350 and 250°C) to explore main effect and interaction differences between these two fixed factors, for each burn treatment. To meet the assumptions of this parametric test, each dataset (all of which were positively skewed) was transformed by taking the logarithm of each data point (Wheater and Cook 2000). All transformed datasets passed the Kolmogorov–Smirnov test for normality except the 'burnt' sample heated to 250°C, which had a bi-modal distribution linked to a small number of very slow settling particles (see Discussion for explanation). Hence, in this case the test was run twice to both include and exclude this specific dataset, thereby assessing the sensitivity of test outcome to bimodality in the burnt-250°C sample. Data were processed using the Minitab statistical analysis package, version 15.

Table 1. Settling velocities (cm s^{-1}) for each effective particle size class for field soils of contrasting temperature impact and organic matter content where uncertainty shown represents the standard error of five repeat runs

Aggregate size class (μm)	Unburnt surface soil	Severely burnt surface soil	Unburnt subsurface soil
360	0.76 ± 0.07	1.89 ± 0.39	2.73 ± 0.30
185	0.61 ± 0.03	1.36 ± 0.29	2.58 ± 0.42
95	0.20 ± 0.05	0.67 ± 0.20	0.57 ± 0.06
49	0.10 ± 0.02	0.21 ± 0.06	0.14 ± 0.02
25	0.02 ± 0.01	0.09 ± 0.03	0.03 ± 0.01

Results

Composite particle settling velocity

Within the field condition samples (i.e. unburnt surface, burnt surface and unburnt subsurface material that had not been subjected to an experimental burn), the settling velocity of each effective particle size class (Table 1, Fig. 2*a*) was observed to be lowest in the unburnt material for all size classes. The settling velocity of burnt material was consistently higher than unburnt surface material for all size classes. Unburnt subsurface material showed the highest settling velocities. All soil types showed the

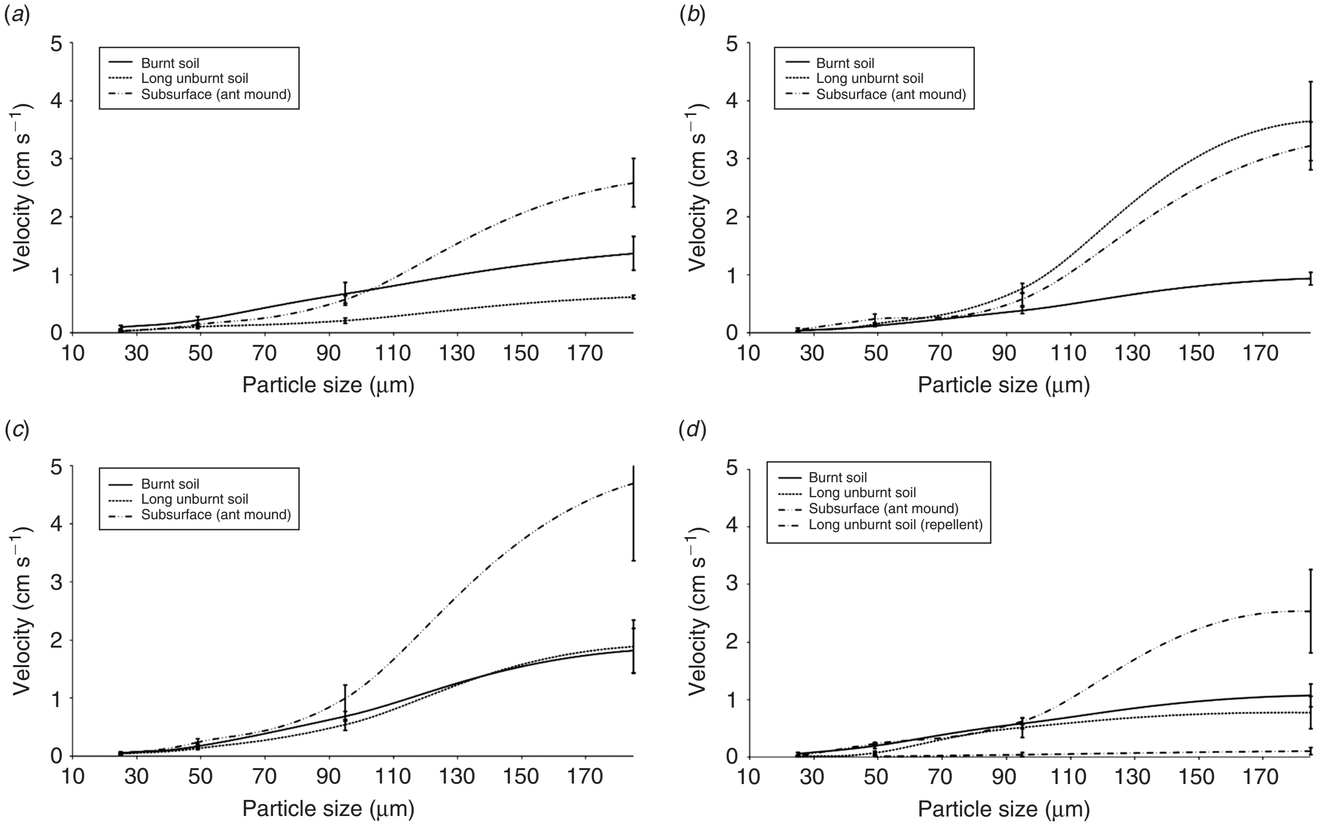

Fig. 2. Particle settling velocities for the experimental soils: (*a*) no experimental burn, experimental burn at (*b*) 550°C, (*c*) 350°C and (*d*) 250°C, where error bars relate to the standard error of the mean for five independent settling experiments.

expected increase in settling velocity with particle size. Unburnt surface, burnt surface and unburnt subsurface soil had loss on ignition (%) values of 30–60, 10 and 10%, respectively.

The influence of the experimental burning on each of the three soil types is illustrated in Fig. 2*b–d*. Burning at 550°C (Fig. 2*b*) increases the settling velocity of unburnt surface material to match that of the unburnt subsurface, which is largely unaffected. The material that had been burnt naturally in the field was also unaffected by experimental heating. At 350°C, the unburnt surface material acquires settling characteristics similar to those of the field-burnt material, which showed little change. Similar results were seen for the material burnt at 250°C although, owing to strong water repellency, the previously unburnt surface sample was initially observed to form large fluffy flocs with a very low settling velocity (Fig. 2*d*). Once equilibrated with water, this material settled in a more similar manner to the previously burnt material as observed at 350°C (although as noted earlier the frequency distribution showed bimodality owing to a small number of very low velocity observations).

Output from the two-way ANOVA analysis (Table 2) indicates that particle size exerts a significant control on settling velocity in all sample datasets, with all P-values at 0.00. A significant difference between settling velocity of the different original burn severity classes is, however, only seen in the field-state soils ($P = 0.00$) and the samples burnt experimentally at 250°C. In these two samples, there is also significant interaction between the factors ($P = 0.01$ and 0.02 for field and 250°C-burnt samples, respectively) implying particle size controls on settling are augmented by certain heating conditions. Original burn severity exerts no significant influence on settling velocity in the materials burnt at higher experimental temperatures 350 and 550°C. Here, particle size is the only control.

Effective particle size distribution

The higher experimental burn temperatures (350 and 550°C) led to a slight fining of the effective particle size distribution of the previously unburnt surface soil material (Fig. 3*a*) whereas at the lower burn temperature (250°C), the effective particle size distribution was observed to coarsen with the greatest change seen in the water repellent material that had not equilibrated with water. The previously burnt material showed no such increase in effective particle size at 250°C (Fig. 3*b*); the unburnt subsurface material showed a slight coarsening (Fig. 3*c*).

Total and 'plant-available' phosphorus

There was no significant difference in acid-soluble total phosphorus concentration between the experimental soils following burning at different temperatures (Table 3). The proportion of phosphorus that was plant-available, however, increased with experimental burn temperature in accord with recent

Table 2. Output from two-way ANOVA test of settling velocity against 'particle size' and 'original burn severity' for each experimental burning treatment (550, 350 and 250°C)

	d.f.	*MS*	*F*	*P*-value
(*a*) Field soils				
Particle size	4	68.21	121.89	0.00
Burn severity	2	2.09	20.61	0.00
Interaction	8	1.10	2.77	0.01
(*b*) 550°C				
Particle size	4	46.07	21.57	0.00
Burn severity	2	1.30	1.42	0.25
Interaction	8	1.12	0.64	0.74
(*c*) 350°C				
Particle size	4	51.20	21.15	0.00
Burn severity	2	1.32	1.45	0.24
Interaction	8	1.12	0.61	0.77
(*d*) 250°C				
Particle size	4	61.18	43.01	0.00
Burn severity	2	2.72	10.17	0.00
Interaction	8	1.57	4.60	0.00
(*e*) 250°C[A]				
Particle size	4	21.94	32.41	0.00
Burn severity	1	2.94	11.15	0.00
Interaction	4	1.40	3.50	0.02

[A]Excluding 'burnt' dataset that failed the Kolmogorov–Smirnov test ($P = 0.032$).

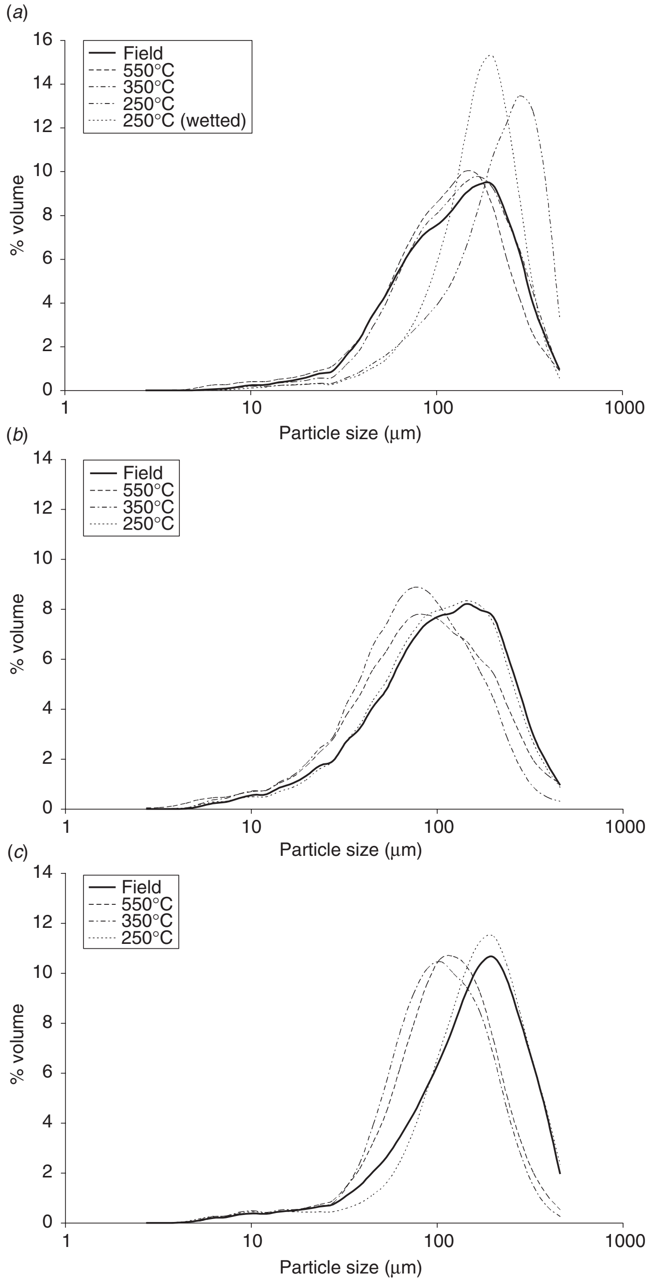

Fig. 3. Effective particle size distributions for (*a*) long unburnt surface soil, (*b*) previously burnt surface soil and (*c*) unburnt subsurface soil following each experimental burn experiment.

observations from burnt soil in the Evrotas River Basin, Greece (Blake *et al.* 2008).

Discussion

The influence of heating on effective particle size and particle settling velocity

The observed increase in settling velocity in burnt field material when compared with long unburnt material (Fig. 2*a*) reflects the observations of Blake *et al.* (2007) who indicated that burnt aggregated particles in this environment are denser than their unburnt counterparts owing to higher organic content within the latter. The high settling velocities of unburnt subsurface material imply that there are few water-stable aggregates in this material and the measurements made are linked to primary particles. This is in accord with the low organic matter content of this material, which is functional in binding soil aggregates in surface material (Piccolo and Mbagwu 1999). The variability in response of particle settling velocity to the different experimental temperatures (Table 2) suggests that the binding mechanism responsible for modifying existing aggregates into dense and robust fire modified water-stable aggregates occurs at a relatively low temperature. Following heating at 550°C, the previously unburnt material assumes the settling behaviour of the subsurface material (Fig. 2*b*), which itself is unaffected by the heating, in terms of settling velocity. This implies that rapid vaporisation of organic material at a high temperature destroys organic bound aggregates within the soil, and subsequent soil-settling behaviour is controlled by primary particle size only (Table 2*b*, *c*).

Previously burnt material shows a slight reduction in settling velocity albeit close to the error margin suggesting that structural modifications due to natural wildfire are preserved during this second experimental burn. At lower temperature burns (Fig. 2*c*, *d*), the settling behaviour of the previously unburnt material is modified to reflect that of the naturally burnt material suggesting the structure has been modified in a similar way to the natural wildfire. Temperatures below 350°C lead to distillation and carbonisation of organic volatiles and resins, reflected in the enhanced water repellency of soil (cf. Doerr *et al.* 2004).

Table 3. Mean total and 'plant-available' phosphorus for each burn experiment

	Field	250°C burn	350°C burn	550°C burn
Total phosphorus (mg kg^{-1})	5308 ± 2676	8154 ± 1486	8651 ± 3198	7315 ± 3318
'Plant-available' phosphorus (mg kg^{-1})	6 ± 1	58 ± 16	100 ± 33	155 ± 33

It is proposed that carbonisation of volatiles coating existing aggregates acts to fuse the composite particles rendering them water stable, hence lower temperature burns augment the effect of particle size on settling velocity through formation of robust composite particles (Table 2*d*, *e*). Owing to the high water repellency status of this material, finer particles readily clump into water-repellent flocs, which are held in suspension until equilibrated with water, after which they settle rapidly.

The presence of organic matter and soil temperature are main controls on settling behaviour observations within these experiments. At higher experimental temperatures, rapid combustion of organic material including volatile oils and resins leads to disintegration of organic bound aggregates and the effective particle size distribution of the soil fines (Fig. 3). Hence, primary particle size dominates settling velocity behaviour. Lower experimental temperatures lead to distillation and carbonisation of organic volatiles and resins, which assist in the binding of aggregates. This leads to a coarsening of the effective particle size distribution in unburnt material and to a lesser extent the subsurface material, which has a low organic content (Fig. 3). Hence, both burn temperature and particle size exert a control on settling velocity. This implies that the temperature experienced by the original burnt field-condition soil was <350°C. Results have implications for soil erodibility under different burn intensities (cf. Moody *et al.* 2005).

Implications of modified sediment transport for downstream water quality

Since 80% of total phosphorus (TP) in surface soil of this system is associated with the <63-μm fraction and 50% of the <63-μm fraction in the burnt surface becomes aggregated, it can be suggested that up to 40% of TP is bound within the fire-modified aggregated material. This has implications for retention of fine sediment and TP within fine-sand sized aggregated material, which will be readily stored within low-order stream channels (Wilkinson *et al.* 2007). While this can be considered a positive feedback mechanism in that the delivery of sediment associated phosphorus to downstream ecosystems will be delayed, it can also be postulated that post-fire water quality problems may persist for much longer than is currently thought owing to longer-term release of nutrients from degrading aggregated material. Although the concentrations of total phosphorus in burnt and unburnt material are not altered significantly by fire (Table 3) suggesting that much of this nutrient is stored in the mineral component of the soil, the increase in 'plant-available' phosphorus linked to temperature is of some interest in the context of downstream impacts (Rannalli 2004; Lane *et al.* 2008). Further work is required to explore the impact of wildfire on phosphorus speciation in burnt material (cf. Blake *et al.* 2008).

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