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Impacts of wildfire on effective sediment particle size: implications for post-fire sediment budgets

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Abstract Recent work in an Australian catchment has shown that severe wildfires followed by rainstorm events lead to redistribution of topsoil and export of sediment to the local river network. Considering the affinity of nutrients and other contaminants for fine sediment, and the potential for considerable downstream impacts, a sound understanding of the fine-sediment delivery from burnt systems is required. However, past work has shown that fire can modify the particle size distribution of the soil through formation of robust sand-sized aggregates comprising fine clays and silts. Image analysis confirmed the presence of fire-modified soil aggregates in our study area. Analysis of aggregate form and fluvial behaviour showed that fire-modified aggregates are fused, dense and inorganic in nature with settling velocities of an order of magnitude faster than unburnt soil aggregates or classic riverine flocs. This implies an increased potential for storage of nutrient-rich fine sediment within slope units, flood plains and river channels. The unusual behaviour of these composite particles should be considered in the construction of post-fire fine-sediment budgets.

Key words aggregate; Australia; fine sediment; fire; nutrients; sediment storage

INTRODUCTION

Significant redistribution of soil and sediment can occur within river basins following wildfire events, particularly when the destruction of vegetation cover by fire is followed by intense rainstorm events (Elliot & Parker, 2001; Luis *et al.*, 2003; Shakesby *et al.*, 2003; Blake *et al.*, 2004). Nutrients and other trace elements have a strong affinity for fine sediment particles (Horowitz, 1991) and their offsite transfer can impact downstream water quality. These impacts can be quantified through construction of post-fire sediment budgets which can assist in monitoring and future management of post-fire sediment redistribution events.

When attempting to construct sediment budgets in river basins, the physical properties of particles, particularly size, are an important consideration. Past research has shown that burning can significantly reduce the clay content of a soil with a corresponding increase in sand-sized particles (Dyrness & Youngberg, 1957) implying aggregation of fine particles into coarser composite particles. Conversely, some studies have shown no significant change in soil aggregate size distribution following burning (Garcia-Corona *et al*., 2004). More recently, Ulery & Graham (1993) used scanning electron microscopy (SEM) techniques to identify the presence of medium sand-sized (250–500 μm) aggregates in a range of severely burnt soils from California, USA, where geochemical analysis suggested bonding was in part due to the formation of poorly crystalline aluminosilicates and amorphous Si and Al from kaolin decomposition during burning. Giovannini & Lucchesi (1997) provide further evidence of alteration to aggregate binding mechanisms during burning. They suggest that in an experimentally burnt soil (a Lithic Xerocrept), alteration of Fe and aluminosilicates lead to fusion of the aggregates into robust particles with greater aggregate stability than their unburnt equivalent. Other studies have indicated similar mechanisms for increased post-fire aggregate stability (e.g. Ternan & Neller, 1999) although soil water repellency can also be important (Mataix-Solera & Doerr, 2004).

Despite these recent advances in understanding of aggregate modification during burning, work to date has not considered the role of fire-modified aggregates in altering the effective particle size of mobilized sediment and its implications for the transport and fate of fine-sediment. The transport of fine (<63 μm) cohesive sediment particles as coarser non-cohesive sand-sized grains has important implications for sediment and nutrient storage in slope and channel environments and how these may be incorporated into sediment budgets.

Consequently, this work aims to explore the presence, composition and fluvial behaviour of fire-modified aggregates in burnt soils from the major water supply catchment of Sydney Australia. We test the hypothesis that: (a) fire-modified soil aggregates behave similarly during fluvial transport and deposition to coarser discrete grains, and (b) fire-modified soil aggregates behave differently during fluvial transport to unmodified unburnt aggregates.

STUDY AREA

This study was undertaken in the drainage basin of Little River, a tributary of the Nattai River, which in turn is a major contributor to Lake Burragorang, Sydney's principal water supply reservoir (Fig. 1). The drainage basin landscape is underlain by Hawksbury sandstone and has been described as a plateau–gorge terrain (Shakesby *et al*., 2003). Soils in the region are classified as Lithosols and Earthy Sands (Stace *et al*., 1986) or Rudosols and Tenosols (Isbel, 1996). The area is forested by a variety of native eucalypt species. During December 2001 and January 2002, the study area was severely burnt by wildfire, triggered by a series of lightning strikes, leaving slopes bare and susceptible to erosion. Between January and May 2002, a series of significant rainstorm events lead to mobilization of soil from the slopes and notable transport of burnt sediment downstream (Blake *et al*., 2004).

METHODS

Samples of burnt soil were collected from the slopes of the Blue Gum Creek drainage basin (Fig. 1) that had undergone high burn severity, but minimal erosion (Shakesby *et*

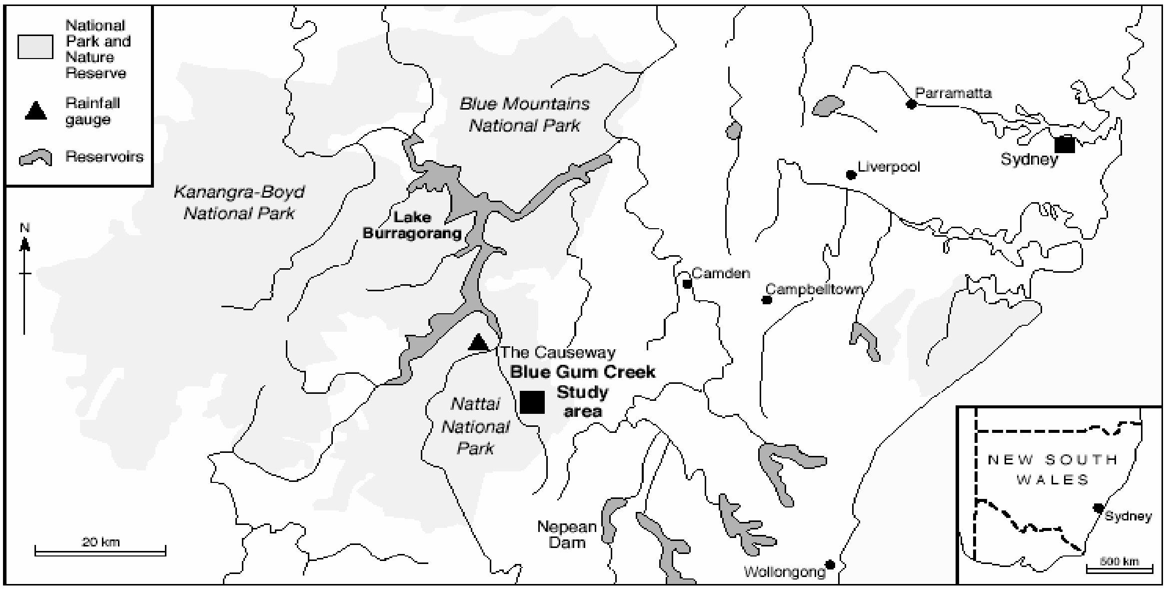

Fig. 1 Location of the study area.

al., 2003). Samples (125) of up to 50 g in mass were collected from 0.5-m^2 areas and thoroughly mixed to create a spatially-integrated bulk sample of the burnt area (cf Ulery & Graham, 1993). Subsamples were then extracted from this for the analytical procedures described below. To compare the nature of these slope particles to those in mobilized and transported material, samples of downstream sediment were collected from within-channel and overbank deposits of the higher order Little River, at distances of between 0.5 and 10 km downstream from the burnt area.

The following analytical procedures were then undertaken:

(a) To determine the presence of fire-modified aggregates in the burnt soil, samples were visually examined using conventional optical microscopy (COM) and environmental scanning electron microscopy (ESEM).

(b) The effective and absolute particle size distributions of the burnt soil samples were determined using a Zeiss Axiovert 100 microscope interfaced with an image analysis system (Northern Exposure^{TM}) following the method described by Droppo (2001). In brief, approximately 0.5 g of untreated burnt soil was settled onto a plankton chamber microscope slide to permit the particle size distribution of 5000 particles to be determined using image analysis software. The procedure was repeated following disaggregation of the sample by intense sonication, allowing the primary particle distribution to be determined.

(c) A further subsample of burnt soil was analysed for aggregate size, settling velocity, density and porosity using a 2.5 l settling chamber interfaced with a stereoscopic microscope, CCD camera, SVHS VCR and Northern Exposure^{TM} software (Droppo, 2001). In this procedure, individual grains were tracked as they passed through the microscope field of view, allowing determination of grain diameter (using image analysis software) and settling velocity by comparison of particle position between video frames. These data were used to calculate particle density and velocity as described in Droppo *et al.* (1997).

(d) To explore the relationship between particle size and geochemical properties within the mobilized sediment, a large subsample (approx. 2 kg) was fractionated into size fractions of <10, 10–20, 20–40, 40–63, 63–125, 125–250 and 250–500 μm, using sieving and settling techniques. These fractions were air died at 35°C and then analysed for major and minor element geochemistry by X-ray fluorescence spectrometry (XRF).

RESULTS AND INTERPRETATION

Observation of burnt soil samples via COM indicated the presence of a small portion of unburnt aggregates, identifiable by inclusion of unburnt organic matter. Figure 2 shows COM images of unburnt (Fig. 2(a)) and burnt soil (Fig. 2(b)) aggregates and ESEM images of the same unburnt and burnt particles, respectively (Fig. 2(c) and (d)). The texture of the natural composite particle (Fig. (2a)) indicates its friable nature—these aggregates readily disintegrate into primary particles during handling. The ESEM image (Fig. 2(c)) gives a similar impression of a friable particle where organic, possibly fungal (Leppard, personal communication), binding materials can also be seen. In contrast, the COM and ESEM images (Fig. 2(b) and (d)) of the burnt aggregate show its

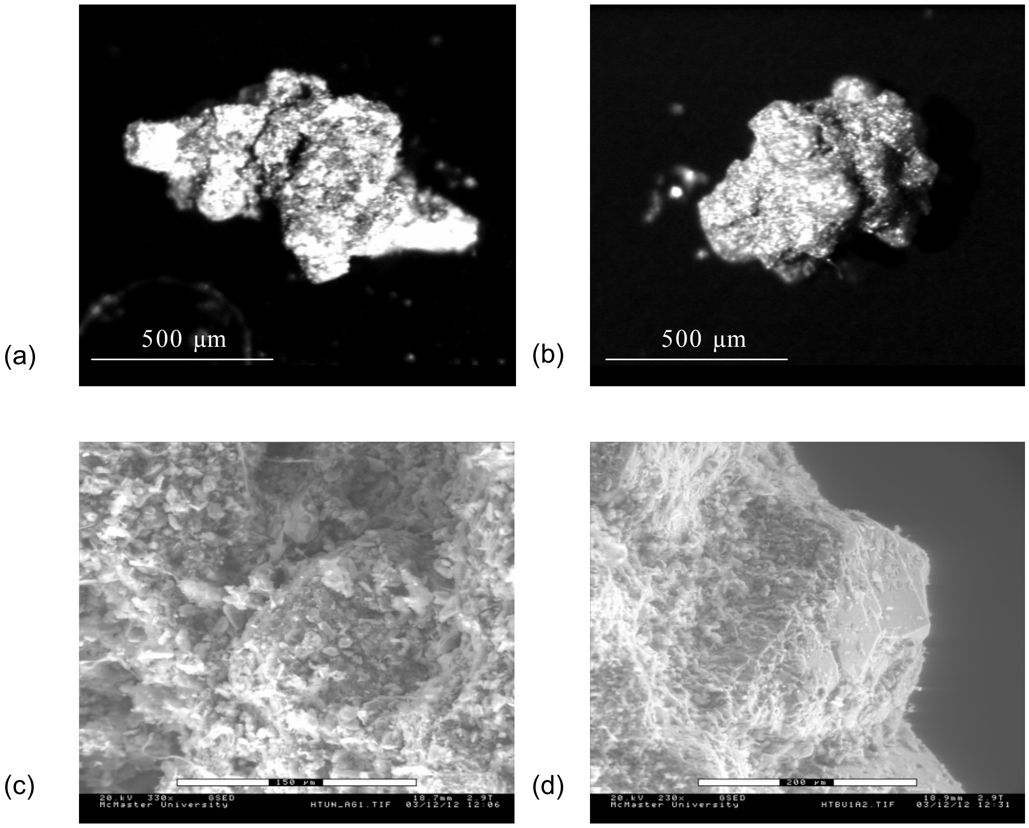

Fig. 2 COM images of: (a) an unburnt unmodified soil aggregate and (b) a fire-modified soil aggregate of similar effective particle size; ESEM images of (c) the unburnt aggregate surface showing discrete particle composition and organic binding materials and (d) the “fused” crystalline surface of the robust fire-modified aggregate.

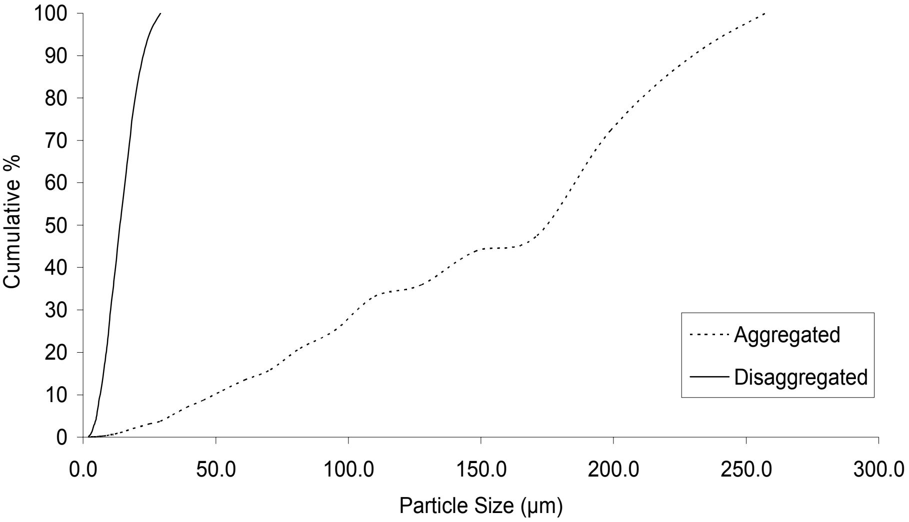

Fig. 3 Particle size distribution of a burnt soil sample before and after mechanical disaggregation

surface to be fused and non-friable. Organic components are not visible and elemental analysis (using an energy dispersive spectroscopy attachment to the ESEM) shows a mineral dominated composition. Direct microscopic observation of natural unburnt aggregates revealed a more porous "fluffy" texture compared to the burnt aggregates.

Figure 3 shows the particle size distribution for a subsample of burnt soil before and after disaggregation. As a compromise between range and resolution at the lower particle size range, an upper limit of 250 µm was used for software particle selection. The aggregate distribution places approximately 70% of the sample (by volume) above 125 µm, while in contrast, when disaggregated, the entire distribution falls below 50 µm. This indicates the presence of aggregates within this burnt soil subsample and further, the fine nature of their component primary parts.

Figure 4 shows the calculated density of particles (in excess of the density of water) plotted against effective particle size, as determined using the settling column apparatus described above. It should be noted that sand grains were operationally excluded from the analysis owing to their rapid settling velocities. Whilst an anticipated negative relationship between particle size and density is observed (reflecting the greater volume of pore space within larger aggregates) the relationship is distorted by the presence of a secondary group of particles, which are of a consistently lower density in relation to particle size. We believe these represent the small proportion of soil aggregates that remained unaffected by the influence of fire, as observed visually by COM, and hence either contain significant organic material or a greater volume of pore space/water. In contrast, the burnt aggregates are fused, inorganic and denser than their unburnt counterparts. Differences in the calculated porosity of the two sample populations are shown in Fig. 5. Unburnt composite particles have a greater porosity than burnt particles of similar size, indicating that during the burning process pore space is lost as particles become fused. As a result, burnt aggregates settle faster than the unburnt aggregates, implying they will be transported less far.

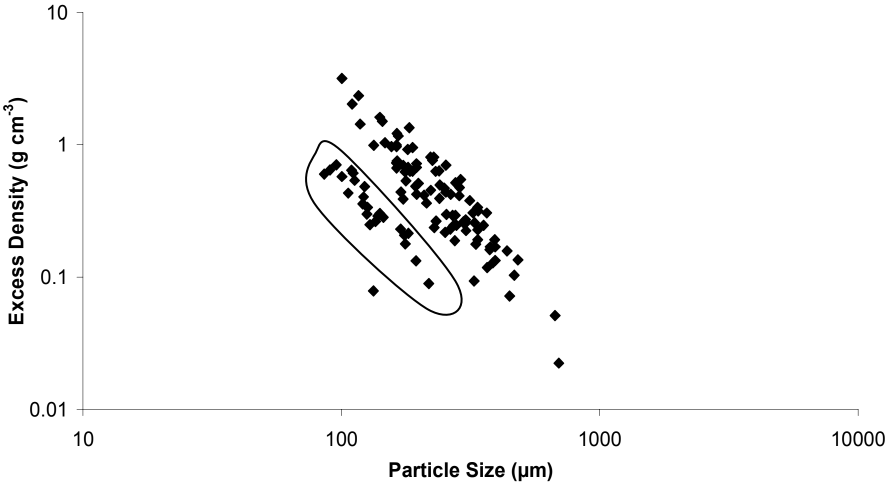

Fig. 4 Aggregate density plotted against particle size, showing two populations: unburnt (circled) and burnt aggregates.

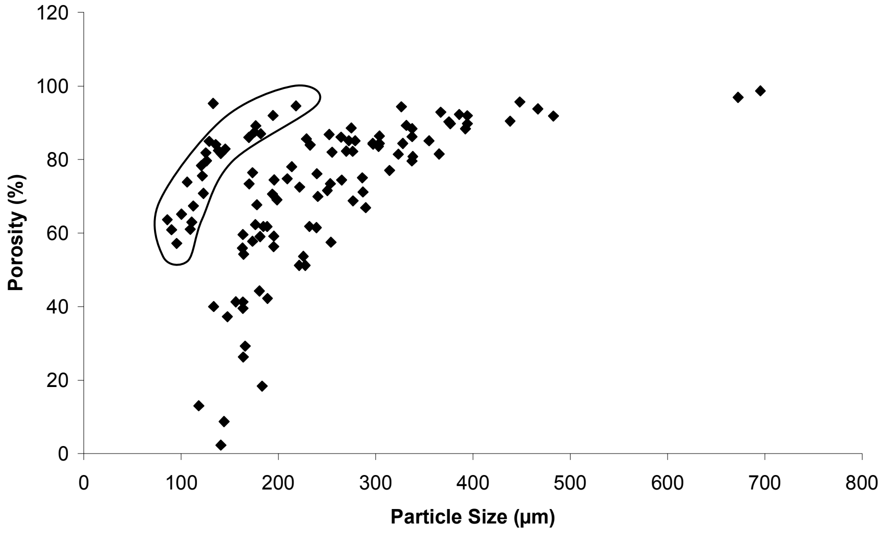

Fig. 5 Aggregate porosity plotted against particle size, showing two populations: unburnt (circled) and burnt aggregates.

The nutrient concentration of the particle size fractions of mobilized sediment (collected from post-fire deposits in the downstream river channel) is shown in Fig. 6. The pattern of distribution of both total phosphorus (given as P_20_5 wt%) and total potassium (K_20 wt%) shows a deviation from the expected particle size relationship of these elements (cf. Horowitz, 1991). Instead of a steady exponential increase in elemental concentration with decreasing particle size, anomalously high concentrations can be seen between particle sizes 250 and 40 µm. We suggest that these higher concentrations correspond to the presence of robust aggregates within these size ranges, a hypothesis which is supported by COM observation of fused, aggregated particles in the sample.

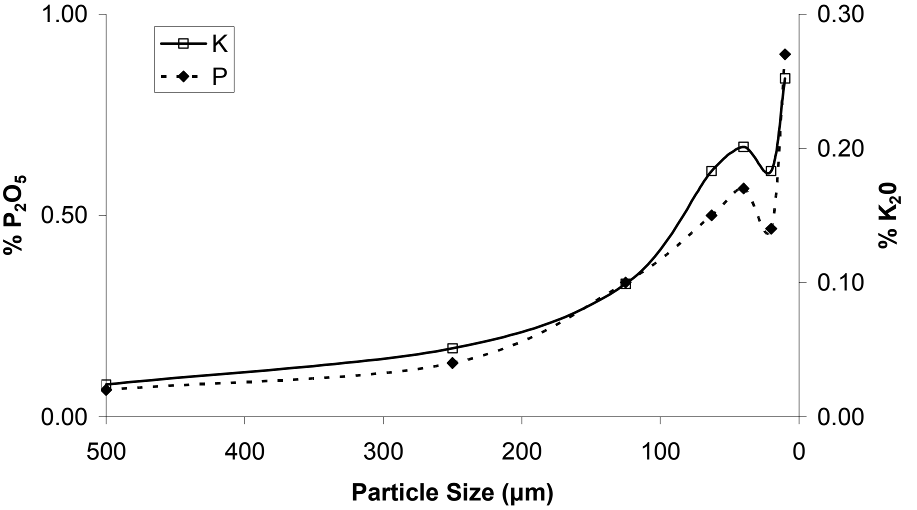

Fig. 6 Nutrient content of the particle size fractions of a downstream sediment sample, suggesting the effect of composite particles in the 40–250 µm fractions.

PERSPECTIVE

The results of this study indicate that fused soil aggregates are present in the burnt soils of the water supply catchments of Sydney as reported by other workers for similar burnt environments. Exploration of the fluvial behaviour of these particles has not previously been undertaken and shows that these aggregates behave differently to both their unburnt counterparts and discrete grains of the same size. The presence of burnt composite particles in mobilized and transported sediment demonstrates that they are robust and readily transported. This has important implications for post-fire sediment budgets. In particular, alteration of the effective particle size of mobilized and transported sediment by fire leads to fine sediment particles and associated trace elements being transported as coarser grains. This is likely to result in increased storage of fine sediment in the slope and channel environments (as composites) and thus influences post-fire delivery of sediment-associated nutrients and construction of related sediment budgets. Whilst the geochemical data indicate that composite aggregate particles may be carrying greater concentrations of nutrients than their discrete counterparts of similar size, further work is required to establish the availability of nutrients within these grains. Indeed, the fused nature of the composite particles may well render associated trace elements unavailable. More work is required on the persistence of these aggregates and their breakdown as a result of transport, abrasion, and storage.

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