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3 authors:


Philip J. Noske
University of Melbourne


Patrick NJ Lane
University of Melbourne


Gary James Sheridan
University of Melbourne

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Stream exports of coarse matter and phosphorus following wildfire in NE Victoria, Australia

Philip J. Noske,* Patrick N. J. Lane and Gary J. Sheridan
Department of Forest and Ecosystem Science, Melbourne School of Land and Environment, The University of Melbourne, 221 Bouverie St., Parkville, Victoria 3010, Australia

Abstract:

The temporal change in total phosphorus (TP) export from two burnt upland catchments is reported. Following wildfire in January 2003, two burnt forested headwater catchments (136 and 244 ha) in the East Kiewa valley, Victoria, were instrumented to measure discharge, turbidity and to collect stream water samples. In addition, samplers were positioned in the stream bed at the outlet of each catchment to continuously sample material transported along the bed of the stream. Approximately, every 2 weeks, the material collected by the stream bed samplers was weighed and sub-sampled. The percentage of coarse (>1 and <5 mm in diameter) mineral (including soil aggregates) and organic matter was determined and then analysed for TP. Between the first and third years after fire, sampled coarse matter and associated TP loads decreased by an average of 53% and 62%, respectively. Over the 3-year study, the amount of coarse matter exported during winter/spring decreased considerably, whereas export rates during summer/autumn remained relatively constant. Coarse matter exports were estimated to be approaching pre-fire levels after 3–4 years. Results on total suspended solids (TSS) TP and total dissolved phosphorus (TDP) from a parallel study are incorporated to explore TP partitioning. TP exported with TSS dominated the total TP export loads, with coarse matter TP and TDP each contributing approximately 10% over the study period. Copyright © 2010 John Wiley & Sons, Ltd.

KEY WORDS wildfire; phosphorus export; bedload; sediment; water quality; eucalypt forests

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INTRODUCTION

Wildfire is a natural event that can produce a significant geomorphological and hydrological change to affected landscapes (Shakesby and Doerr, 2006). Numerous studies have shown how fire modifies surface erosion processes through changes to the soil surface properties and surface cover. Fire has been shown to increase soil fertility, aiding the regrowth of vegetation in eucalypt forests in Australia (Polglase *et al*., 1986; Romanya, *et al*., 1994; Tomkins, *et al*., 1991), as the ash bed generated can act as substantial deposit of inorganic phosphorus (Andreu *et al*., 1996; Cade-Menun *et al*., 2000). If this increased supply of phosphorus (P) enters a waterway, the trophic status of streams, rivers and water impoundments within and downstream of a burnt catchment may change.

As discussed by Lane *et al*. (2008a), Australian studies investigating in-stream P concentration and export after wildfire are scarce. Most research into post-fire total phosphorus (TP) export has taken place in coniferous temperate forests across the USA (Wright, 1976; Tiedemann *et al*., 1978; Williams and Melack, 1997; Hauer and Spencer, 1998). Other forest types include boreal (Bayley *et al*., 1992) and tropical (Malmer, 2004). Generally, after wildfire TP concentrations in whole water samples increase between two (Tiedemann *et al*., 1978) and six (Hauer and Spencer, 1998) times, for a period between 2 months (Malmer, 2004) and 4–5 years (Tiedemann *et al*., 1978). In Australia, substantial increases of in-stream loads and concentrations of TP associated with total suspended solids (TSS) were measured by Wilkinson *et al*. (2006) and Lane *et al*. (2008a), with the majority of material transported during rainfall events. However, the bulk of research on in-stream post-fire P exports focuses on dissolved forms of P. Generally, results show the in-stream concentration of dissolved P to increase two to three times after fire (Wright, 1976; Tiedemann *et al*., 1978; Hauer and Spencer, 1998) with levels remaining high for up to 5 years (Tiedemann *et al*., 1978).

Post-fire erosion can include significant quantities of coarse material (Leitch *et al*., 1983; Atkinson, 1984; Moody and Martin, 2001a; Lane *et al*., 2006) that may have associated P. Investigating coarse material as a potential source of P is important in predicting the impact that fire may have on downstream ecosystems. In the majority of aquatic environments, P enters in particulate and dissolved forms via surface flow (Correll, 1998). When the stream water velocity drops on entering a water impoundment, transported coarse material and any associated P may be deposited. Considering the dynamic physico-chemical nature of aquatic systems, P may interchange between dissolved forms (which are available to plants) and particulate matter (Syers *et al*., 1973; Correll, 1998). Under certain conditions, P may diffuse from

* Correspondence to: Philip J. Noske, Department of Forest and Ecosystem Science, Melbourne School of Land and Environment, The University of Melbourne, 221 Bouverie St., Parkville, Victoria 3010, Australia.
E-mail: pnoske@unimelb.edu.au

the bed sediments across a concentration gradient (Correll, 1998; Reddy *et al*., 1999; McDowell *et al*., 2002; Haggard and Sharpley, 2007). Therefore, particulates that settle as bed sediment have potential to act as a P source or a sink (Keup, 1968; Reddy *et al*., 1999; Haggard and Sharpley, 2007). A large increase in P concentration was measured in North Carolinian river when increased flow produced turbulence, which resuspended stream bed material (Keup, 1968). As residence timing of coarse material in streams exceeds that of suspended matter (Reneau *et al*., 2007), increased P concentrations have the potential to be more sustained, extending the impact of wildfire.

A series of studies have investigated the in-stream export of TSS after wildfire in the USA (Campbell *et al*., 1977; Helvey, 1980; Moody and Martin, 2001b,a) and Australia (Brown, 1972; Lane *et al*., 2006; Wilkinson *et al*., 2006). Most studies at the catchment scale found TSS loads to increase after fire. Catchment exports of coarse material after wildfire have received less attention. Some estimates have been made by measuring the rate of sedimentation in water impoundments. These studies have been conducted in pine plantations in South Africa (Scott and Van Wyk, 1990), and coniferous forests in Colorado (Moody and Martin, 2001a,b) and New Mexico (Lavine *et al*., 2006; Reneau *et al*., 2007). During the first year after fire, Scott *et al*. (1998) and Scott and Van Wyk (1990) reported a fourfold increase in bedload export, with 30% of the total sediment exported being bedload. During the 3-year post-fire period, which included two flash floods, Moody and Martin (2001a) measured large quantities (250 000 m^3) of coarse sediment deposited in a reservoir. Lavine *et al*. (2006) and Reneau *et al*. (2007) measured elevated rates of erosion over the first 5 years after fire, with coarse grained sediment contributing on average approximately 30% of the total sediment transported (over 80% in the fourth and fifth years). In a small stream in Canada, Beaty (1994), using a stream bed sampler, reported transport rates to increase 20-fold in the second year after the fire. During abnormally high rainfall in a coniferous forest with sandy soil in Arizona, Campbell *et al*. (1977) estimated 1560 kg/ha (12 600 kg) of suspended sediment and 2770 kg/ha (22 000 kg) of bedload sediment to be exported during the first 6-month post-fire. The importance of the often unmeasured bedload component in post-fire erosion is illustrated by these studies.

The effect of wildfire on soil properties and hydrology within small headwater catchments in north-eastern Victoria and the export of sediment and major plant nutrients have been explored by Lane *et al*. (2006), Sheridan *et al*. (2007) and Lane *et al*. (2008a). This paper aims to expand those studies by investigating the export of coarse matter (>1 and <5 mm in diameter), which includes mineral primary particles, soil aggregates and organic matter (OM), and the role that coarse matter plays in TP export after wildfire.

SITE DETAILS

Research was conducted in two adjacent catchments located in the East Kiewa valley in north-east Victoria, Australia (Figure 1). Slippery Rock Creek (136 ha) and Springs Creek (244 ha) have previously been described in Lane *et al*. (2006) and Sheridan *et al*. (2007). The elevation ranges from 620 to 1380 m in the Springs Creek catchment and from 660 to 1520 m in the Slippery Rock Creek catchment, with slope gradients >24° occurring over 55% of the area (Papworth *et al*., 1990). The geology of both catchments is highly faulted gneiss and quartz diorite, with small areas of granodiorite in the Slippery Rock Creek catchment. The soils are friable brown gradational clay-loams and sandy clay-loams grading to coarse sand C horizons generally <1·5 m deep (Hough, 1983). Shallow uniform soils are found on the spurs with deeper black organic to sandy-clay loams in drainage lines. Generally, the soils are high in iron and OM content, and show strong aggregation with a low susceptibility to slaking and erosion.

The catchments are predominantly vegetated with *Eucalyptus delegatensis* RT Baker (Alpine Ash) in almost pure stands, most of which are mature to over-mature (>100 years old). These stands make up 70% of the area in Springs Creek catchment and 62% of the Slippery Rock catchment. At lower elevations (<1100 m), the

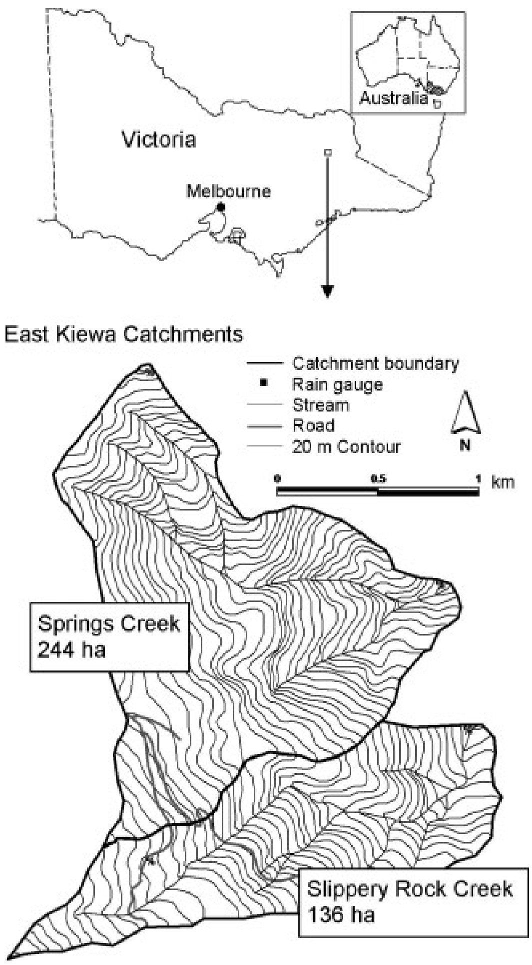

Figure 1. The location of the East Kiewa research catchments

vegetation is dominated by mixed *Eucalyptus* spp. with the majority being Broad-leafed Peppermint (*Eucalyptus dives*), Narrow-leafed Peppermint (*Eucalyptus radiata*) and Candlebark Gum (*Eucalyptus rubida)*. The riparian zone contains a tall understorey, usually with a dense cover of tree ferns (*Dicksonia antarctica*) in the gullies, flanked by a dense fern and low shrub stratum (Papworth *et al*., 1990).

As part of a previous study investigating the impacts of timber harvesting in these catchments, discharge and TSS were measured between 1978 and 1987. 'Bedload' (coarse material) that was trapped in the weir dam was measured intermittently (Papworth *et al*., 1990). Average annual rainfall was 1832 and 1989 mm at Slippery Rock and Springs Creek field sites, respectively (Papworth *et al*., 1990). The Australian Government Bureau of Meteorology measured rainfall between the years of 1939 and 1988 at Bogong village which is at a similar elevation as the base of the catchments and $<1\cdot5$ km away: the annual average was 1818 mm with a winter/spring dominant distribution. Intense summer thunderstorms are common in this area, with snow fall occurring at elevations >1100 m in winter and spring, and more intermittently at lower elevations.

On 15 January 2003, both catchments were burnt by a wildfire causing severe crown scorch. This fire resulted in a high proportion of the *E. delegatensis* being killed and the understorey and ground cover vegetation being completely burnt. The details of the fire severity are presented in Lane *et al*. (2006).

METHODS

Annual data are presented on a water-year basis, which is from 1 May to 30 April. Seasonal data are presented on a 3-month basis, with summer being December to February, autumn March to May, winter June to August and spring September to November.

Catchment instrumentation

A detailed description of field instrumentation other than the stream bed sampler is provided in Lane *et al.* (2006) and Lane *et al.* (2008a) and is only briefly described here. Rainfall, stream discharge and stream turbidity were measured at 15 min intervals. Rainfall was measured at both gauging sites using tipping-bucket rain gauges. Discharge was measured through a triangular broad-crested weir at Slippery Rock Creek and a Parshall flume at Springs Creek. Turbidity was measured *in situ* at each site using Mindata model 2600 turbidity probes with a range of 0–1000 NTU. At Slippery Rock Creek during the 2006/2007 water year, there was difficulty in measuring discharge due to a cracked weir wall resulting from exceptionally dry conditions; for this water-year discharge data were not used for interpreting the results.

Coarse matter

Field. Steam bed samplers were constructed near the stream gauging points of each catchment. Each sampler was positioned at the end of a 1 m wide and approximately 4 m long concreted flow structure, which consisted of two stone and concrete walls on either side of a flat concrete pad. This structure was designed to evenly channel the stream water over a 1 m wide sampler intake, which consisted of a 1 m long square rolled hollow piece of steel sealed at each end, with five 5 mm wide and 100 mm long evenly spaced slots. When set in place, the slots were facing upwards and parallel to the stream flow. The outlet consisted of a 50 mm pipe that was located in the middle of the intake facing down slope. Water, sediment and other matter that entered the slots flowed via the pipe by gravity to a 200 l settling tank, which was located below the stream sampler. The tank continually over-flowed with water, and any coarse matter captured by the sampler settled and collected in the tanks. On average, each tank was emptied every 2 weeks (site service interval) by carefully draining the tank using an outlet at the base. The outlet was connected to a filter that prevented coarse matter escaping while draining. The material that accumulated in each tank was thoroughly mixed by hand, weighed and a 2 l sample taken and sent to the laboratory. This procedure took place from the time of the sampler installation on 1 May 2003 to the end of the study in March 2007. A total of 175 two litre samples were collected. The sampler was designed to ensure the amount of material that collected in the tanks could be safely measured, mixed and sampled by field staff working alone.

Laboratory. Each 2 l sample (representing each site service interval) was stored at 4 °C and divided into four approximately equal portions. One portion was oven dried at 105 °C; this enabled the water content to be determined. The dry mass equivalent of 5–10 g of another portion was sub-sampled and wet sieved to 1 mm. Material greater than 1 mm in diameter was deemed to be coarse in nature. This included mineral particles, soil aggregates and OM. This was similar to the sediment sizing used by Gomi and Sidle (2003). Wet sieving was conducted by gently pouring Milli RO (purified) water over the sample on a 1 mm sieve. The remaining >1 and <5 mm coarse matter was oven dried at 60 °C, weighed and stored till further analysis. From this analysis, the percentage of coarse matter present in the material captured by the stream bed sampler was determined.

A known mass of approximately $0\cdot5$ g of each sieved coarse matter sample was analysed for TP using a modified perchloric and nitric acid digest procedure for soils with OM (Sommers and Nelson, 1972). The digestion proceeded for 30 min at 210 °C or until the matter was completely digested, and only a grey-white substance remained. The remaining solution ($\sim$3 ml) was made up to 25 ml using distilled water, mixed and allowed to settle. P content was then determined on the resulting solution using an inductively coupled plasma-atomic emission spectrophotometer (ICP-AES, Varian, Vista Axial, Varian, Palo Alto, CA, USA).

Total carbon (TC) percentage was determined on each sample of coarse matter by grinding a sub-sample to 0·5 mm, oven drying at 105 °C and analysing by Dumas combustion using a C–N analyser (LECO CHN-2000). Loss-on-ignition (LOI) was conducted on a sub-set of these samples (114) over the range of TC percentages. Samples were heated at 550 °C for 3 h (Howard and Howard, 1990; De Vos *et al*., 2005) in a muffle-furnace (Tetlow, Melbourne, Victoria, Australia), the mass lost by heating was used as an estimate of the OM percentage (Ball, 1964; Baldock and Skjemsad, 1999).

The quantity of mineral sediment was determined on a sub-set of 99 coarse matter samples across the range of TC percentages. Up to 10 g of oven dried coarse matter was combined with 980 ml of distilled water, 10 ml of 10% sodium hexametaphosphate and 10 ml of 1 M sodium hydroxide in a 1250 ml cylinder. The cylinders were shaken end-over-end for 16 h at 20 rpm, breaking down any soil aggregates into fine mineral particles. The OM and the fine mineral particles were then separated from the coarse mineral sediment by flotation. Cylinders were repeatedly filled with water and then after a few seconds decanted, this was repeated until all OM and fine particles were removed. The material was then sieved to 1 mm, with the remaining material consisting entirely of mineral sediment, which was oven dried at 105 °C then weighed.

Using the mineral sediment and LOI percentage, the soil aggregate percentage in each sample was estimated using Equation (1). The soil aggregate percentage is the percentage of fine mineral particles <1 mm in diameter that were contained within aggregates and dispersed by end-over-end shaking.

$$\text{Soil aggregate }\% = 100 - (\text{Mineral sediment }\% + \text{LOI }\%) \quad (1)$$

Load measurements and calculations. At the Slippery Rock Creek catchment outlet, a weir dam with a capacity of 150 m^3 trapped all the eroded coarse material. The volume of trapped material was measured on four occasions: July 2003, January 2004, February 2005 and May 2006 by mapping the depth of the weir dam on a 1 m grid, and subtracting the volume measured from the volume of the weir dam when empty. This was not measured in the fourth water year because of the failure of the weir wall. When the weir was emptied, on July 2003 and May 2006, representative samples of material were taken in 500 ml containers. Water content and bulk density were determined on the samples, which enable the estimation of the mass of total material from the volume measured.

The percentage coarse matter (>1 mm) was determined by combining the dry weight equivalent of 50 g of each sample. Approximately, 300 g was wet sieved to 1·0 mm, >1 mm material was dried and weighed. This enabled the percentage coarse matter that accumulated within the weir dam between the periods of emptying to be calculated. The results from July 2003 samples were applied to January 2004 weir measurements, and an average between the results sampled for the 2 years was applied to February 2005 weir measurements.

The routine measurements of material trapped by the stream bed sampler complemented the total annual weir measurements at Slippery Rock Creek, and enabled an estimation of total mass of coarse matter exported from both catchments between weir measurements. This estimation was made by fitting an exponential curve to the cumulative mass of coarse matter that accumulated within the weir dam, against the number of days since the fire. From this curve, it was possible to estimate the total cumulative mass of coarse matter that was exported for any given sample day since the fire (i.e. the date stream bed sampler tanks were serviced). The measured cumulative mass of coarse matter that was sampled by the stream bed sampler at Slippery Rock Creek then was fitted to the values estimated from the curve by applying a multiplying factor to generate the best fit. Because the same method of stream bed sampling was used at each catchment, this multiplying factor was also applied to Springs Creek to provide an estimate of total coarse matter loads.

TP load calculations. The coarse matter TP loads, sampled by the stream bed samplers, were calculated for each service interval by multiplying the concentration of coarse matter TP by the mass of coarse matter captured. The quantity of TP that was trapped in the weir dam at Slippery Rock Creek was estimated using the same TP concentrations. A weighted average TP concentration was calculated and then applied to the mass of coarse fraction material measured within the weir dam. This produced an estimation of the total mass of coarse fraction TP exported from Slippery Rock Creek catchment. The same method of curve fitting was applied to coarse matter TP data to estimate TP loads for both catchments between weir measurements.

Suspended and dissolved matter

Stream turbidity was measured *in situ* at both catchments using turbidity probes. To reduce turbulence, the probes were mounted in stilling tanks. The off-takes from the streams to the stilling tanks were covered by a strainer that excluded any particles over 1 mm in diameter. As described in Lane *et al.* (2006), turbidity measurements were used as a surrogate for TSS. Stream water was sampled from the stilling tanks using Sigma Streamline 900 portable samplers, which were programmed to collect multiple 1 l water samples during rainfall (storm) events on both rising and falling limbs of the hydrograph. Laboratory analysis was conducted for both TSS TP and TDP within these water samples. The laboratory procedures are detailed in Lane *et al.* (2006) and Lane *et al.* (2008a), with TSS being <1 mm and >0·45 µm and dissolved matter <0·45 µm in diameter.

TSS TP and TDP loads were calculated for using the methods described in Lane *et al.* (2008a). Loads were separated into base flow and storm event flow, by manually delineating discrete storm events from the

15 min rainfall, stream discharge and stream turbidity data. Storm events were identified by the beginning of rainfall which resulted in an increase in either stream discharge or turbidity (i.e. the sediment delivery rate). The end of a storm event was defined as when the sediment delivery rate had declined substantially from the peak usually to within 10% of the pre-storm value. Storms in close succession and multiple peaked storms were not included as single events; these were separated based on the occurrence of receding flow, turbidity and the timing of subsequent rainfall.

RESULTS

Rainfall and discharge were similar for the first three water years at both catchments, whereas, there was a decrease in both rainfall and discharge during the 2006/2007 water year (Table I). Data analysis ceased at both sites at the start of March 2007 due to partial burning of each catchment; therefore, 2006/2007 water year was shortened by 2 months. No discharge data were collected at Slippery Rock Creek in 2006/2007 water year due to the failure of the weir wall. From rainfall intensity-duration data, Lane *et al*. (2006) concluded that rainfall patterns during the first two water years post-fire were not statistically different to pre-fire.

Table I. Total rainfall and stream discharge

Year	Slippery Rock Creek		Springs Creek	
	Rainfall (mm)	Discharge (mm)	Rainfall (mm)	Discharge (mm)
2003/2004	1825	1206	1658	694
2004/2005	1993	1441	1681	896
2005/2006	1548	1122	1594	783
2006/2007[a]	449	—	433	260

[a] Not a full water year, May 2006 to March 2007.

Table II. Annual coarse matter mass captured by stream bed samplers

Date	Slippery Rock Creek	Springs Creek
	Total coarse fraction (kg)	Total coarse fraction (kg)
2003/2004	131·5	72·7
2004/2005	73·1 (−44·4%)	80·7 (+11·1%)
2005/2006	46·0 (−65·0%)	43·1 (−40·7%)
2006/2007[a]	1·9 (−98·6%)	5·3 (−92·7%)

Percentage change compared with first water year post-fire is given in parentheses.
[a] Not a full water year, May 2006 to March 2007.

Stream bed sampler material

Coarse matter. Coarse matter trapped by the stream bed samplers consisted of coarse textured mineral (e.g. mineral primary particles and soil aggregates) and OM (e.g. charcoal and charred plant material). The samplers were designed to collect an integrated fortnightly sample of material for physical and chemical analyses. The amount of material collected provided an approximation of the amount of coarse matter transported, rather than an exact flow-weighted proportion, because on occasions the stream bed sampler slots became partially blocked and the sampling efficiency differed during different rates of stream flow. However, changes in the amount of coarse matter trapped over time since the fire, provides a relative measure of the temporal change in coarse matter exports (Table II), particularly when calibrated against weir measurements at Slippery Rock Creek.

Independent variables of total and peak rainfall, and total and peak discharge were investigated to identify which variables were most highly correlated with the coarse matter captured by the stream bed samplers (Table III). The independent variables were log-normally distributed and the data were transformed by taking the $\log_{10}$ of the raw data. To identity any temporal change

Table III. Coefficient of determination for relationships between sampled coarse matter mass, and rainfall and discharge variables for each water year

Variable	Slippery Rock Creek water year				Springs Creek water year			
	2003/2004	2004/2005	2005/2006	2006/2007	2003/2004	2004/2005	2005/2006	2006/2007
Log total rainfall	0·44*	0·65***	0·68***	—	0·25*	0·70***	0·77***	0·32
Log max 30 min rainfall	0·09	0·09	0·35**	—	0·08	0·13	0·52***	0·00
Log max 1 h rainfall	0·15	0·21*	0·35**	—	0·15	0·27**	0·54***	0·01
Log max 2 h rainfall	0·30	0·36**	0·42***	—	0·17	0·43***	0·57***	0·00
Log max 24 h rainfall	0·47*	0·49***	0·66***	—	0·26*	0·48***	0·73***	0·02
Log total discharge	0·27*	0·55***	0·57***	—	0·29***	0·46***	0·54***	0·26
Log max 30 min discharge	0·13	0·61***	0·79***	—	0·44***	0·61***	0·75***	0·54*
Log max 1 h discharge	0·18	0·63***	0·79***	—	0·49***	0·62***	0·76***	0·54*
Log max 2 h discharge	0·24	0·65***	0·79***	—	0·53***	0·63***	0·76***	0·52*
Log max 24 h discharge	0·41**	0·71***	0·82***	—	0·58***	0·66***	0·76***	0·63***

Years 2003/2004 to 2005/2006: $n = 23–26$; 2006/2007: $n = 14–15$.
* p-value $<0·05$.
** p-value $<0·01$.
*** p-value $<0·001$.

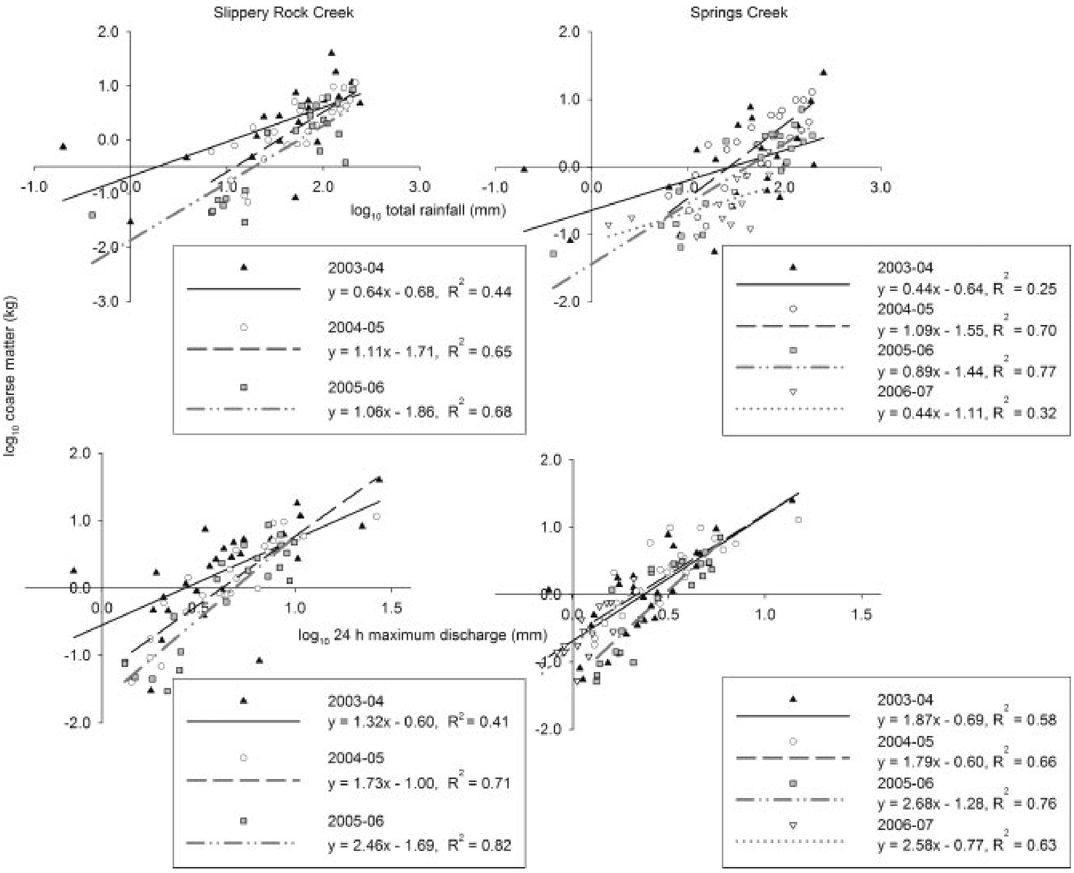

Figure 2. Mass of coarse matter trapped by the stream bed samplers per site service interval, as a function of the total rainfall or 24 h maximum discharge that occurred during the site service interval

in these relationships, data from each site service interval were separated into water years.

The strongest relationships were between coarse matter sampled and the total rainfall and 24 h maximum discharge (Figure 2). At Slippery Rock Creek the y-intercept decreased with time, demonstrating a reduction in the amount of coarse matter transported from the catchments with the equivalent total rainfall and 24 h maximum discharge, especially between the first and third water years. The increasing gradient shows that a reduction in coarse matter exports occurs only where the independent variables are lower than where the lines intersect, which includes the majority of data points. The data presented between total rainfall and coarse matter sampled for Springs Creek are more ambiguous, and it is difficult to identify any temporal change, although generally the y-intercept decreased compared with the first year. The relationship between 24 h maximum discharge and coarse matter produced a similar result for the first two water years after fire, with a reduction in the y-intercept occurring during the third year. There was only a limited range of discharge values during the fourth drought-affected year.

Coarse matter sampled, 24 h maximum discharge and the total rainfall during each site service interval were separated into seasons, and are presented in Figure 3. Generally, the maximum mass of coarse matter captured at each site occurred during the winter of each year, which coincided with the annual peak in rainfall and the large increase in discharge between autumn and winter. The transport of coarse matter was higher in the winter of the first water year after fire at Slippery Rock Creek, coinciding with the first significant post-fire rainfall.

Coarse matter TP. Coarse matter TP concentrations fluctuated over time in both catchments and ranged from 0·3 to 0·6 mg/g. Figure 4 shows the data grouped in the same fashion as Figure 3, with each data point representing the average coarse matter TP concentration from the previous 3 months. There was no correlation between coarse matter TP concentration and any of the discharge or rainfall variables shown in Table III. However, the data presented in Figure 4 suggest that TP concentration peaks during autumn when the 24 h maximum discharge and total rainfall were at an annual minimum.

The TP concentration varies by a factor of 2 between the lowest and highest values over the period of the study. However, the mass of coarse matter varies between 40 and 70 times (Figure 3) and therefore the amount of material transported, not the TP concentration, is driving the TP loads presented in Table IV. As a consequence, the relationships between $\log_{10}$ coarse matter TP and $\log_{10}$ of the independent variables produced similar results to the coarse matter analysis (Table V), with total rainfall and maximum 24-h discharge producing the strongest

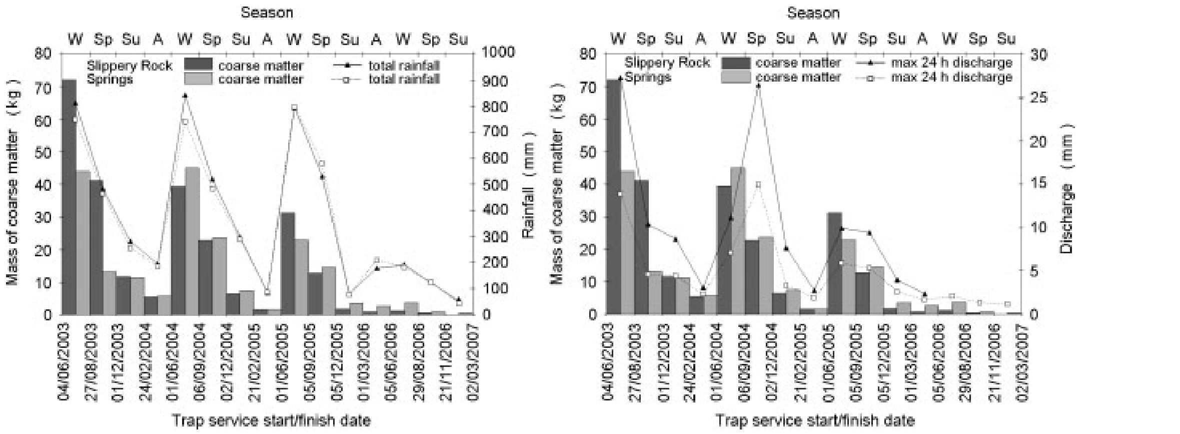

Figure 3. Seasonal total mass of coarse matter trapped by the stream bed samplers, and the seasonal total rainfall or 24 h maximum (max) discharge

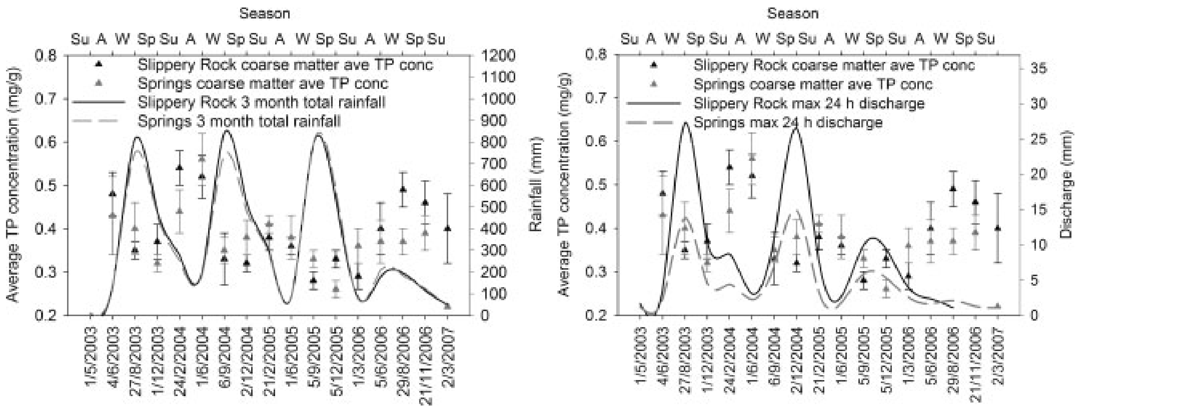

Figure 4. Coarse matter seasonal average total phosphorus concentration (TP conc), and seasonal total rainfall or maximum (max) 24 h discharge

Table IV. Stream bed sampler coarse matter TP loads

Date	Slippery Rock Creek sampled coarse fraction TP load (g)	Springs Creek sampled coarse fraction TP load (g)
2003/2004	47·8	26·5
2004/2005	33·6 (−51%)	27·2 (+3%)
2005/2006	13·8 (−71%)	12·7 (−52%)
2006/2007[a]	0·9 (−98%)	1·8 (−93%)

Percentage change compared with first water year post-fire is given in parentheses.
[a] Not a full water year May 2006 to March 2007.

coefficients of determination. For brevity, the plots are not shown as they are similar to those shown in Figure 2. Similarly, the oscillations that are shown in Figure 3 were mirrored by the coarse matter TP results.

Coarse matter composition and TP. For both catchments, the $\log_{10}$ TC and $\log_{10}$ LOI percentage in the coarse matter were correlated against $\log_{10}$ TP percentage (Figure 5a and b) producing strong relationships. In addition, strong relationships were produced when the estimated soil aggregate percentage was correlated against TP percentage (Figure 5d). These correlations indicated that most of the TP in the coarse matter is associated with the carbon-based material and eroded soil aggregates.

A temporal trend between the average coarse matter TC and TP percentage (Figure 6) existed, supporting the relationships shown in Figure 5. The first point in Figure 6 represents the average of 1 month of sampling; three sample collection times occurred during this autumn period. This was because the stream bed samplers were not installed until May 2003. In relation to rainfall and discharge, TC concentration in the coarse matter behaved in a similar manner to TP concentration (Figure 4). In addition, mineral sediment percentage was positively correlated with discharge and rainfall variables. When data were split into water years, the strongest correlations were between mineral sediment and maximum 24 h discharge, with r^2 values ranging from 0·2 to 0·6.

Load measurements and calculations

After the first year post-fire, there was a rapid reduction in the mass of dry material and coarse matter being trapped in the weir dam. It follows that there was a reduction in the rate of coarse matter being eroded and transported (Table VI).

At Slippery Rock Creek, the percentage coarse matter in the sampled material from the weir dam decreased between 2003 and 2006, the percentage coarse matter trapped by the stream bed samplers followed a similar trend (Table VII). The decline in the transport of coarse matter and associated TP can be seen in the plots of

Table V. Coefficient of determination between coarse matter TP mass sampled, and rainfall and discharge variables for each water year

Parameter	Slippery Rock Creek water year				Springs Creek water year			
	2003/2004	2004/2005	2005/2006	2006/2007	2003/2004	2004/2005	2005/2006	2006/2007
Log total rainfall	0·41*	0·69***	0·67***	—	0·23*	0·66***	0·81***	0·02
Log max 30 min rainfall	0·10	0·10	0·35**	—	0·09	0·16	0·52***	0·05
Log max 1 h rainfall	0·17	0·23*	0·35**	—	0·12	0·31**	0·55***	0·05
Log max 2 h rainfall	0·34	0·37**	0·41***	—	0·14*	0·46***	0·59***	0·03
Log max 24 h rainfall	0·49*	0·50***	0·64***	—	0·24*	0·46***	0·78***	0·00
Log total discharge	0·22*	0·46***	0·56***	—	0·23**	0·46***	0·47***	0·25
Log max 30 min discharge	0·12	0·59***	0·78***	—	0·41***	0·61***	0·73***	0·48*
Log max 1 h discharge	0·17	0·61***	0·77***	—	0·46***	0·61***	0·73***	0·48*
Log max 2 h discharge	0·23	0·63***	0·78***	—	0·49***	0·62***	0·74***	0·47*
Log max 24 h discharge	0·38**	0·68***	0·80***	—	0·50***	0·63***	0·76***	0·69***

* p-value $<0{\cdot}05$.
** p-value $<0{\cdot}01$.
*** p-value $<0{\cdot}001$.

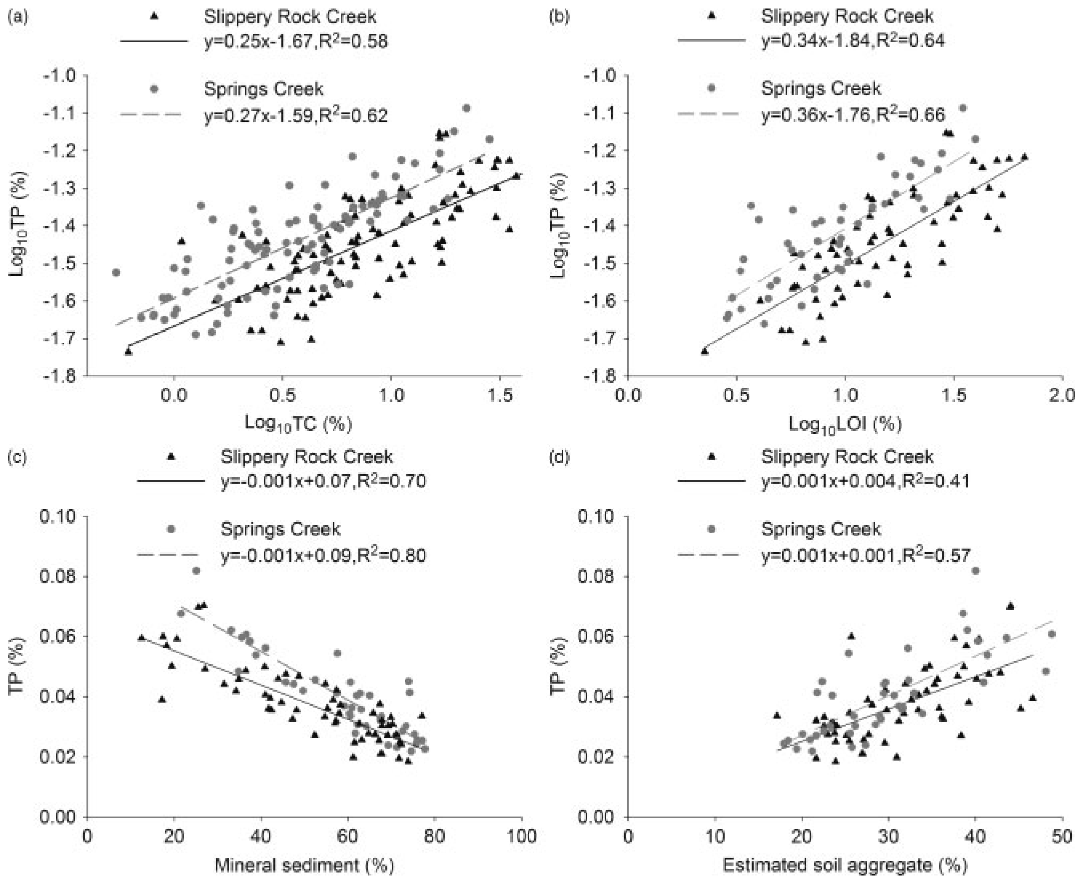

Figure 5. Regressions between total phosphorus (TP) percentage and various coarse matter constituent percentages, (a) total carbon (TC), (b) mass loss on ignition (LOI), (c) mineral sediment, (d) estimated soil aggregate

Table VI. Material measured in weir dam at Slippery Rock Creek

Time since fire (decimal years)	Date of measurement	Total weir dry material (t)	Total weir dry material (t/ha year)	Total weir coarse matter (t)	Total weir coarse matter (t/ha year)
0·5	31 July 2003	135	1·84	45	0·61
1·0	7 January 2004	114	1·68 (−9%)	38	0·56 (−9%)
2·1	9 February 2005	99	0·67 (−63%)	26	0·18 (−71%)
3·3	23 May 2006	30	0·18 (−90%)	6	0·04 (−94%)

Percentage change compared with first water year post-fire is given in parentheses.

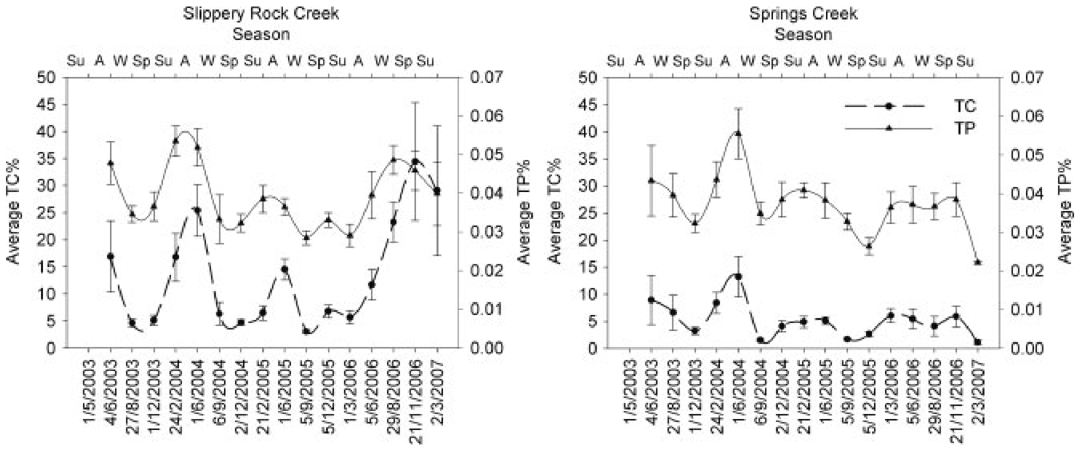

Figure 6. Coarse matter seasonal average total phosphorus (TP) and total carbon (TC) concentrations

Table VII. Percentage coarse matter in samples collected at Slippery Rock Creek

Time since fire (decimal years)	Weir sample (%)	Stream bed sampler average (%)	Stream bed sampler standard deviation
0·5	33	23 (31)	10
1·0		30 (28)	5
2·1		27	5
3·3	20	28	6

Percentage change during major storms in the filled weir dam is given parentheses.

the cumulative masses trapped within the weir dam and sampled by the stream bed samplers (Figure 7a and c). As the coarse matter TP concentration within the coarse matter varied by two, similar cumulative plots were produced. These plots show:

- the seasonal oscillations in the coarse matter captured by the stream bed samplers, indicated by a change in the regression line gradient (Table VIII);
- the gradients of the cumulative lines during winter/spring reduce with time, which was when the majority of coarse matter was being transported and sampled;
- the gradients are relatively consistent during the summer/autumn period;

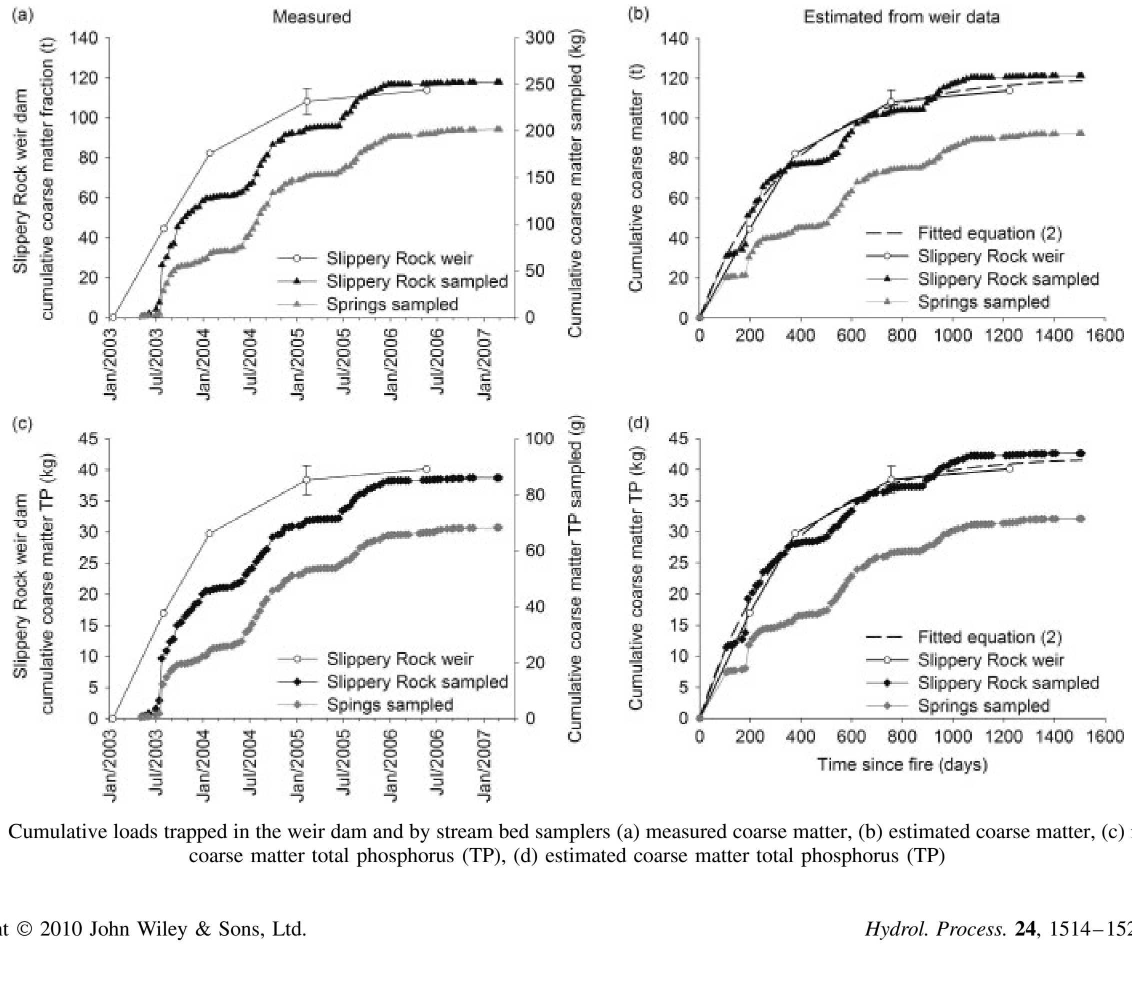

Figure 7. Cumulative loads trapped in the weir dam and by stream bed samplers (a) measured coarse matter, (b) estimated coarse matter, (c) measured coarse matter total phosphorus (TP), (d) estimated coarse matter total phosphorus (TP)

Table VIII. Seasonal gradients of cumulative coarse fraction TP

Start date	Finish date	Season[a]	Slippery Rock Creek		Springs Creek	
			Gradient	R^2	Gradient	R^2
1 May 2003	3 June 2003	Su/A	0·06	0·9	0·03	0·6
3 June 2003	1 December 2003	W/Sp	0·25	0·9	0·14	0·8
1 December 2003	1 June 2004	Su/A	0·05	0·7	0·04	0·9
1 June 2004	2 December 2004	W/Sp	0·11	1·0	0·13	1·0
2 December 2004	1 June 2005	Su/A	0·02	0·8	0·03	0·7
1 June 2005	5 December 2005	W/Sp	0·08	1·0	0·06	1·0
5 December 2005	5 June 2006	Su/A	0·00	0·9	0·01	0·6
5 June 2006	21 November 2006	W/Sp	0·00	0·9	0·01	0·7
21 November 2006	2 March 2007	Su/A	0·00	0·7	0·00	1·0

[a] Su/A is summer and autumn combined and W/Sp is winter and spring combined.

Table IX. TP loads

Year	Slippery Rock Creek			Springs Creek		
	Coarse matter TP (kg/ha year)	TSS TP (kg/ha year)	Dissolved TP (kg/ha year)	Coarse matter TP (kg/ha year)	TSS TP (kg/ha year)	Dissolved TP (kg/ha year)
2003/2004	0·13 (5%)	2·14 (90%)	0·12 (5%)	0·04 (3%)	1·03 (90%)	0·08 (7%)
2004/2005	0·06 (8%)	0·58 (77%)	0·11 (15%)	0·04 (7%)	0·43 (77%)	0·09 (16%)
2005/2006	0·04 (9%)	0·31 (74%)	0·07 (17%)	0·02 (6%)	0·28 (78%)	0·06 (6%)
2006/2007[a]	0·00	—	—	0·00	0·10	0·03

Percentage contribution to loads is given in brackets.
Coarse matter TP calculated from fitted curve.
[a] Not a full water year May 2006 to March 2007.

- that the amount of coarse matter that collected within the weir dam follows a very similar trend to the coarse matter trapped by the stream bed sampler, giving confidence in the coarse matter sampling apparatus and procedure.

To calculate the sub-annual total mass of coarse matter and associated TP exported from the catchments, a curve using Equation (2) was fitted to the cumulative weir dam measurements as follows:

$$y = a(1 - \exp^{(-bx)}) \qquad 0 \geq x \leq 1507 \qquad (2)$$

where y is the cumulative coarse matter or associated TP; x is the days since fire; a and b are 120·4 and 0·003, respectively, for coarse matter; and a and b are 41·98 and 0·003, respectively, for associated TP, both producing an r^2 of 0·99.

The curves allow the cumulative mass of coarse matter and associated TP to be estimated for the date of each site service interval (days since fire) at Slippery Rock Creek. Cumulative coarse matter and coarse matter TP measurements from the stream bed sampler at Slippery Rock Creek were then fitted to these values by applying a multiplication factor determined using the least squares method of data fitting. The multiplication factors for coarse matter and associated TP data were 358 and 362, respectively. The samplers were installed 106 days after the fire, so the mass of coarse matter and coarse matter TP that was exported prior to stream bed sampler installation was estimated using Equation (2).

The same type of stream bed sampler was used at both sites; consequently, the same multiplication factor used at Slippery Rock Creek was applied at Springs Creek. The ratio between the mass of coarse matter and coarse matter TP mass at Springs Creek and Slippery Rock Creek during the first stream bed sampler service interval was used to calculate the mass of material exported from Springs Creek catchment during the first 106 days. The fitted data and curves calculated from Equation (2) are shown in Figure 7b and d, and calculated coarse matter TP loads are presented in Table IX.

Suspended and dissolved matter

Results for the average concentrations and export loads of TSS TP and TDP mg/l from 2003/2004 to 2005/2006 are presented in Lane *et al.* (2008a). TSS TP concentrations (mg/g) were averaged on a 3-month seasonal basis and are presented for Slippery Rock Creek and Springs Creek in Figure 8. Each point in the figures is the average concentration for the previous 3-month period. In both catchments, there was an initial flux of TSS with a higher concentration of TP than subsequent samples, particularly at Slippery Rock Creek. Coarse matter TP concentrations are plotted to illustrate the difference between the two particle sizes and their potential to contribute to the export of TP. The low concentrations of TSS TP occurred at Springs Creek during a period of low flow where no storm samples were collected between 1 March 2005 and 1 June 2005.

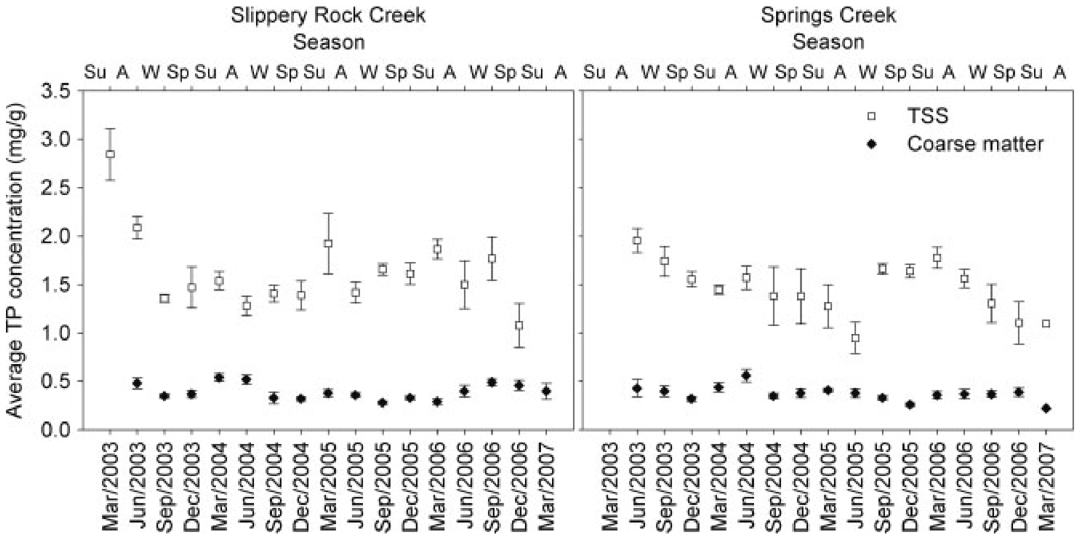

Figure 8. Seasonal average particulate total phosphorus (TP) concentration

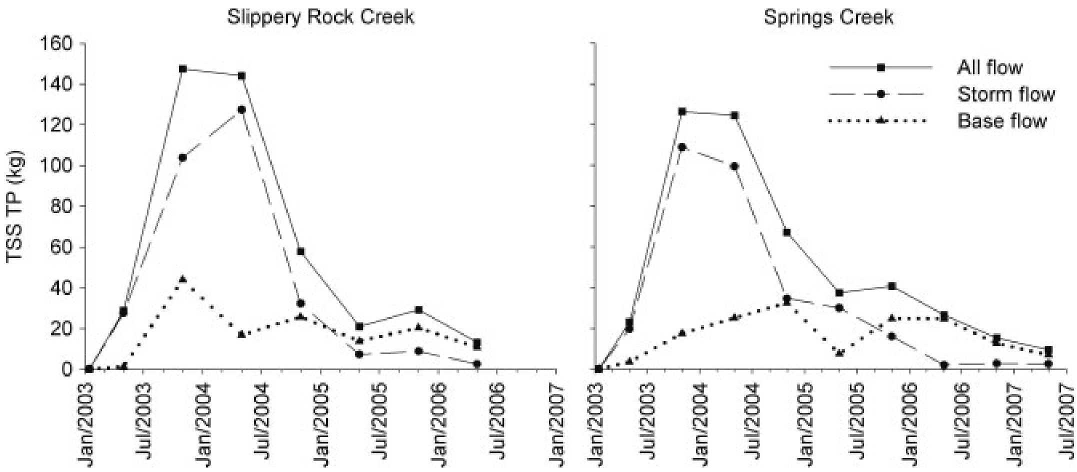

Figure 9. 6 monthly loads of total phosphorus (TP) associated with total suspended solids (TSS), separated into stream flow type

The reduction in annual TSS TP load is shown in Figure 9 on a 6- month basis. Initially, TSS TP loads in both catchments were dominated by storm flows (Lane *et al*., 2008a). The contribution of TSS TP loads for event and base flow is similar after 2–3 years post-fire, with the TSS TP loads being dominated by the base flow component after this time.

TP exports

The relative contribution of each mode of TP transport was dominated by the TSS TP for the majority of the time (Figure 10). The relative contribution by the coarse matter appears to be greater in the first few months after fire in both catchments; however, this was during times when there was minimal TP export via any mode of transport.

The total mass of coarse matter TP was estimated by the curve fitting method. The results presented in Figure 11 and Table IX suggest that the contribution of coarse matter TP was between 5% and 6% of all the TP exported. This was similar or less than what was exported as TDP, which contributed between 8% and 12% with around 84% associated with TSS.

DISCUSSION

Coarse matter

Few studies have investigated the effect of wildfire on the transport of coarse matter. Of the publications that are available, there is difficulty in comparing the results, as often it is unclear which particle sizes were classified as coarse, and if all the materials that collected in the samplers and stream flow control structures were measured. In an earlier study by Papworth *et al*. (1990), weir dam ‘sediment’ volume and mass were measured at Slippery Rock Creek, and erosion rates estimated to be 0·03 t/ha between May 1981 and March 1982. Therefore, the total dry material and coarse matter export rates were estimated to be 60 times higher during the first year after fire when compared with unburned data (Table VI). This estimate is slightly more refined than that of Lane *et al.* (2006), in which export rates are estimated to increase by

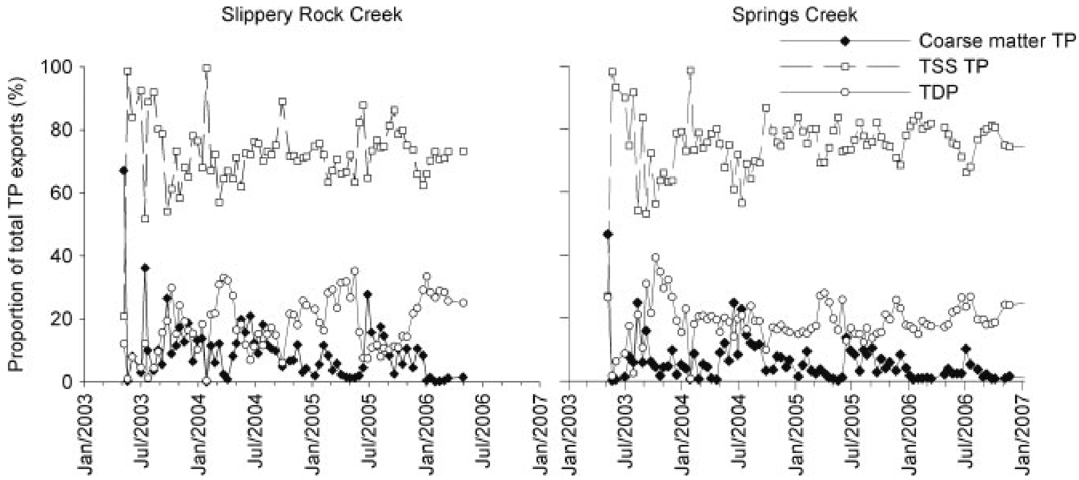

Figure 10. Proportional contribution of each mode of total phosphorus (TP) transport over time since the fire

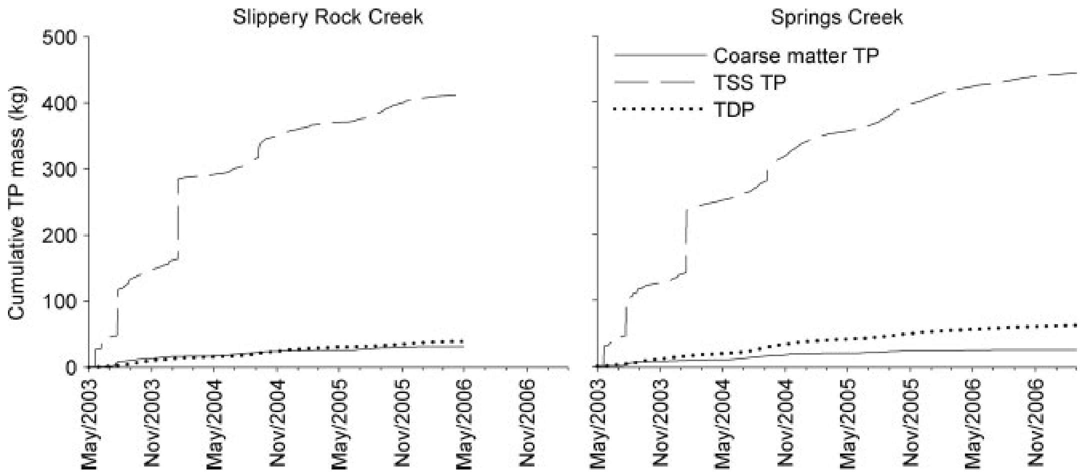

Figure 11. Cumulative total phosphorus (TP) loads, separated into coarse matter total phosphorus (TP), total suspended solids total phosphorus (TSS TP) and total dissolved phosphorus (TDP)

an order of magnitude. In Papworth *et al.* (1990), there was separation between silt, sand and gravel but methods were not discussed. If the sand and gravel fractions were greater than 1·0 mm then the coarse matter erosion rate could be approximated at 0·01 t/ha year. A series of five catchments, which carried a similar undisturbed forest with a lower average rainfall at Reefton in central Victoria, produced an average of 0·05–0·01 t/ha year of total dry 'bedload' (Papworth, 1982). In this study, the erosion rate of coarse matter during the third year was 0·04 t/ha year, which was the same order of magnitude as these studies. Therefore, it could be assumed that the coarse matter erosion rate was approaching pre-fire levels within 3–4 years after fire.

Campbell *et al.* (1977) measured bedload erosion rates at 5·5 t/ha year during the 6 months after a severe fire, compared with 0·01 t/ha year in a moderately burnt forest. Beaty (1994) measured bedload rates at 0·06 t/ha year during the second year after fire with levels reducing to pre-fire estimates after 6 years. Scott and Van Wyk (1990) estimated bedload erosion rate to be 1·8 t/ha year during the first year after fire. In this study, coarse material erosion rates during the first year, which included two large storm events, were less than those measured by Campbell *et al.* (1977) and more than the other studies cited. The recovery time of Slippery Rock Creek catchment was estimated at 4 years, similar to that reported by Beaty (1994).

Similar to the weir measurements, the mass of coarse matter that collected in the stream bed samplers generally reduced with time (Table II). Empirical relationships of variable strength were produced when these data were split into water years, and the mass of coarse matter was plotted against the 24 h maximum discharge and total rainfall (Table III). This gave confidence that the stream bed sampling procedure was providing a good indication of coarse matter exports. Each year after the fire, a greater rate of discharge or rainfall amount was required to transport the same quantity of coarse matter as shown by a decreasing *y*-intercept, particularly at Slippery Rock Creek. Sheridan *et al.* (2007) investigated erosion process in these catchments and concluded that as a result of the very high infiltration potential of these forest soils, any material that entered the stream would be sourced from the riparian zone. Williams and Melack (1997) suggested that the post-fire recovery of riparian vegetation retards material from entering streams, and from vegetation surveys conducted in these catchments, riparian vegetation had recovered by around 80% within 1 year post-fire (Lane *et al.*, 2006). Generally, the coefficient of determination in Figure 2 and Table III increased, which suggest that the movement of coarse matter was more controlled by stream discharge and the amount of rainfall (which were not independent) with time. However, during the first year, external processes such as hillslope failure (de Koff *et al.*, 2006), wind erosion (Raison *et al.*, 1984) or erosion by bio-transfer (Dragovich and Morris, 2002; Smith and Dragovich, 2008) may have contributed to the export of coarse matter, resulting in poorer correlations between coarse matter sampled and tested variables.

In both catchments, the annual 24 h maximum discharge was similar in the first and second years post-fire. However, second year coarse matter sampled at Slippery Rock Creek reduced by 44%, whereas at Springs Creek it increased by 11% (Table II). Lane *et al.* (2006) compared stream flow data pre- and post-fire, and concluded that during the first year a lower increase in flow was measured from Springs Creek (43%) compared with Slippery Rock Creek (68%). However, flow increased by 94% and 68% for Springs Creek and Slippery Rock Creek, respectively, over the second year. Therefore, the total discharge from Springs Creek during 2003/2004 was low in comparison to the following years; this would potentially limit the transport of coarse matter and may explain the differing results between the two catchments.

A large reduction in coarse matter transport can be seen in the third year, but the 24 h maximum discharges that occurred during the third year were less than half that of the previous 2 years' maxima (Figure 3). However, when comparing 24 h maximum discharge during the winter and spring of the third water year to the winter in the second and spring in the first water years (when rates of discharge were similar), there is a substantial reduction in coarse matter sampled. In addition, the annual total rainfall remained relatively consistent throughout the first 3 years post-fire, and importantly throughout the first three winters when the majority of material was sampled. During the 2006/2007 water year, it was difficult to determine if the decrease in coarse matter captured was due to decreased rainfall and flow, or a result of catchment recovery.

The seasonal oscillation in coarse matter sampled indicated that either there was some accumulation of coarse matter in the stream channel during the drier months or the movement of material was transport-limited through low rates of discharge. The subsequent decrease in coarse matter sampled during the spring may be due to the depletion of source material, even though the volume of discharge and the 24 h maximum flow was higher in the spring compared with the winter in 2003/2004 and 2004/2005.

TP associated with coarse matter

TP concentration. Figure 4 shows an inverse oscillating pattern between average 3-month TP concentrations and 3-month 24-h maximum discharge and also 3-month total rainfall. This may be due to different materials being eroded during different rainfall amounts and subsequent rates of discharge. Pacini and Gächter (1999) observed lower concentrations of P in sediment that was mobilized in streams during the higher rates of discharge. This was in agreement with the data collected from these catchments, with a positive correlation between mineral sediment and 24-h maximum discharge. However, in comparison to the fluctuation in coarse matter loads, TP concentrations were relatively constant over the duration of this study and appeared to be independent of the length of time since the fire (Figure 4).

There are robust positive relationships between TP percentage, and TC, LOI, soil aggregates and negative relationship with mineral sediment (Figure 5). This suggests that a majority of the TP transported was with OM and soil aggregates. The same oscillating pattern in Figure 4 can be seen for TC percentage in Figure 6, showing the percentage by mass of organic material within the coarse matter transported decreased with an increase in flow and rainfall. There is evidence in other studies of finer particles being fused by fire to produce tough aggregates <1 mm in diameter (Blake *et al.*, 2005; Blake *et al.*, 2007), with the fine particles which make up the aggregates having a higher affinity for P (English *et al.*, 2005). The contribution of TP from soil aggregates >1 mm is significant.

Sheridan *et al.* (2007) concluded that due to the high variability in the soil saturated hydraulic conductivity within these catchments any infiltration-excess overland flow and transported material entering the stream would be from within several metres of the stream edge. The lack of rill erosion in these catchments (Sheridan *et al.* 2007) suggests that soil aggregates were sourced from the stream bank and riparian area during periods of increased flow. However, a quantitative split of coarse material sampled, between channel and hillslope sources, was not possible from the data in this study.

TP load. The quantity of coarse matter and coarse matter TP sampled followed similar trends in both catchments. Stream bed sampler loads reduced over time, with TP loads reducing by 55% and 65% for Slippery Rock Creek and 6% and 54% for Springs Creek for the second and third winters, respectively, compared with the first winter.

TP partitioning

Total suspended sediment TP concentration. Erosion processes are selective for finer particles, which are more prevalent after fire (Saá *et al.*, 1994; Pacini and Gächter, 1999; Thomas *et al.*, 1999), and can contain a higher P concentration (Raison *et al.*, 1984; Pacini and Gächter, 1999). The average 3-month concentration of

TSS TP (mg/g) remained approximately four times the concentration of coarse fraction TP (mg/g), however, there was no obvious seasonal rainfall or flow driven pattern. During the first 3 months after the fire, there was an initial spike in the concentration of TSS TP (mg/g) compared with the following months, particularly at Slippery Rock Creek (Figure 8). Concentrations then reduced to a similar magnitude to that measured by Hopmans and Bren (2007) from a stream in a nearby undisturbed mixed eucalypt catchment. The initial high concentration of TSS TP (mg/g) was from samples collected during storm events in both catchments. These are thought to be the result of ash and fine soil particles washing into the stream from the riparian zone, and/or the transport of material that was deposited on the stream bed or stream bank during or shortly after the fire.

Total suspended sediment TP load. Lane *et al.* (2008a) measured a reduction in the annual quantity of TSS TP exported from each catchment for each successive year following the fire. After 2 to 2·5 years post-fire, stream base flow was contributing more to the TSS TP load than event flow (Figure 9). Considering that post-fire, the export of TSS TP was driven by the event flow rather than base flow; it is hypothesized that the switch between the major contributing flow types is an indication of when catchment TSS TP exports (and TP exports) have returned to pre-fire levels. This switch occurred even though there was substantial rainfall during the third water year post-fire. Supporting this notion, Lane *et al.* (2008b) estimated pre-fire TSS loads to be 0·17 t/ha year, and during the third water year measured TSS loads of 0·18 t/ha year. Considering TP concentration associated with the TSS was relatively constant after the initial pulse, it could be assumed that during the third water year TSS TP exports had returned to pre-fire levels.

TP exports. For the majority of time, the TP loads exported from both catchments were dominated by the TSS TP (Figure 11), which contributed approximately 81% by mass. The contribution of TP via each mode of transport showed initially that the coarse matter contributed a majority. However, this may be an artefact of the curve fitting exercise or when there was minimal TP export occurring via any mode of transport. The majority of research concerned with in-stream transport of P after fire is focused on dissolved forms, when in this system TDP contributes only around 10% of the TP load. This is similar to the amount of coarse matter TP exported (6%), which is often unmeasured in post-fire research catchment studies.

In comparison to the other modes of TP export, the quantity of TP that is transported with the coarse matter makes a relatively minor contribution to the TP loads exported from burnt forested catchments in the Victorian Alps. However, if pre-fire erosion rates of TP are estimated using the average TP concentrations (mg/g) from this study, and the pre-fire erosion rates from Papworth *et al.* (1990), they would be 0·004 and 0·26 kg/ha year for coarse matter and TSS, respectively. During the first year after fire, Slippery Rock Creek coarse matter TP erosion rate was estimated to be 0·13 kg/ha year, assuming TSS is the dominant mode of TP export, this equates to half the estimated total TP contribution from the catchment in an unburnt state, which is substantial. However, the amount of bioavailable TP (other than TDP) was not determined in this study. To become bioavailable, generally organic and particulate P must be transformed to inorganic forms (Reddy *et al.* 1999). Therefore, it is difficult to predict how the course matter TP loads measured would change the trophic status of receiving lakes and reservoirs. What is known is the sorption and desorption of P from sediment can affect the concentration of P in stream water, especially during flow rates that re-suspend bed sediments (Reddy *et al.*, 1999).

CONCLUSIONS

Compared with pre-fire data coarse matter export rates were estimated to be 60 times higher during the first year after fire, with loads oscillating seasonally with peak stream flow and total rainfall. The quantity of coarse matter was the dominant variable in coarse matter TP exports. Therefore, like coarse matter, it could be assumed that coarse fraction TP exports were approaching pre-fire rates 3–4 years after the fire. It was found that the majority of the coarse fraction TP transported from these catchments was associated with OM which contained large quantities of charred plant material, charcoal and ash, and with eroded soil aggregates. When loads were partitioned between the different transport phases over 3 years, the estimated contributions were coarse matter TP 6%, TSS TP 84% and TDP 10%. From these catchments, TSS was the major contributor to TP loads with the majority transported during event flow. It is hypothesized that the switch to when base flow is contributing more TSS TP than event flow is not only an indication of when catchment TSS TP exports returned to pre-fire rates but also an indication of when catchment TP exports have returned to pre-fire rates. This occurred 2–2·5 years after the fire in these catchments.

From the scale of the fires that have occurred in Victoria, Australia in 2002/2003 (1·3 million ha), 2006/2007 (1·1 million ha) and 2009 (~0·5 million ha), the results of this study show that the increase in P loading to receiving waters could be considerable, increasing the risk of algal blooms. Coarse material may also act as a source or sink for P, prolonging increased P concentrations in receiving waters and the effect of wildfire.

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