Title: Effects of aridity in controlling the magnitude of runoff and erosion after wildfire

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Key points:

- Erosion processes in burned forests can be strongly dependent on aridity-related soil and vegetation characteristics.
- Temporal changes in both sediment availability and surface runoff drive variation in erosion rates during a 5-year recovery period after wildfire.
- In south-east Australia higher surface runoff from forests in more arid locations results in an increased risk of debris flows.

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1. Abstract

This study represents a uniquely high resolution observation of post-wildfire runoff and erosion from dry forested uplands of SE Australia. We monitored runoff and sediment load, and temporal changes in soil surface properties from two (0.2-0.3 ha) dry forested catchments burned during the 2009 Black Saturday wildfire. Event-based surface runoff to rainfall ratios approached 0.45 during the first year post-wildfire, compared to reported values <0.01 for less arid hillslopes. Extremely high runoff ratios in these dry forests were attributed to wildfire induced soil water repellency and inherently low hydraulic conductivity. Mean ponded hydraulic conductivity ranged from 1 to 30 mm h^{-1}, much lower than values commonly reported for wetter forest. Annual sediment yields peaked at 10 t ha^{-1} during the first year before declining dramatically to background levels, suggesting high-magnitude erosion processes may become limited by sediment availability on hillslopes. Small differences in aridity between equatorial and polar-facing catchments produced substantial differences in surface runoff and erosion, most likely due to higher infiltration and surface roughness on polar-facing slopes. In summary the results show that post-wildfire erosion processes in Eucalypt forests in south-east Australia are highly variable and that distinctive response domains within the region exist between different forest types, therefore regional generalisations are problematic. The large differences in erosion processes with relatively small changes in aridity have large implications for predicting hydrologic driven geomorphic changes, land degradation and water contamination through erosion after wildfire across the landscape.

2. Introduction

Changes in erosion rates due to wildfire can result in almost no impact through to extreme impacts that destroy infrastructure, contaminate water supplies, denude soils and alter landforms

[*Moody et al.*, 2013]. This variability is the result of a number of factors including fire intensity, topography, soil properties, forest type and the timing, intensity and quantity of rainfall after fire [*Mackay and Cornish*, 1982; *Shakesby and Doerr*, 2006; *Tomkins et al.*, 2008; *Nyman et al.*, 2011; *Moody et al.*, 2013; *Sheridan et al.*, 2015]. Wildfire has been shown to reduce soil infiltration [*Mallik et al.*, 1984; *Cerdà*, 1998; *Martin and Moody*, 2001; *Onda et al.*, 2008; *Moody et al.*, 2009; *Nyman et al.*, 2010; *Moody et al.*, 2015], surface roughness [*Scott and Van Wyk*, 1990; *Lavee et al.*, 1995] and rainfall interception [*Prosser and Williams*, 1998; *Benavides-Solorio and MacDonald*, 2001].Wildfire may also enhance soil water repellency [*Scott and Van Wyk*, 1990; *Woods et al.*, 2007; *Nyman et al.*, 2010; *Moody and Ebel*, 2012], potentially increasing its persistence [*Doerr et al.*, 2006; *Sheridan et al.*, 2007] and disrupting its natural seasonal oscillation under Eucalypt forests [*Burch et al.*, 1989; *Crockford et al.*, 1991; *Shakesby et al.*, 2003; *Doerr et al.*, 2006; *Shakesby and Doerr*, 2006; *Sheridan et al.*, 2007]. Much of this has already been thoroughly reviewed by numerous authors [*Certini*, 2005; *Shakesby and Doerr*, 2006; *Shakesby et al.*, 2007; *Moody et al.*, 2013]. Variability in erosion response after wildfire is illustrated by comparing *Lane et al.* [2006] who reported first year post-wildfire erosion rates associated with interill processes of only 3 t ha^{-1} y^{-1} following high intensity wildfire, and *Nyman et al.* [2011] where erosion rates associated with debris flows in nearby forests were estimated to produce 10 – 100's of t ha^{-1} per event. Different erosion processes are sensitive to different forcings; interill erosion depends on rainfall energy; rill erosion requires soils that will generate substantial overland flow; runoff generated debris flows require critical thresholds of runoff, sediment supply and slope; and mass failures are sensitive to saturation processes. The key to understanding variability in the erosion response after wildfire is recognising the dominant erosion process, and the inherent properties of the system that determine the chance of an area experiencing erosion events of low or high magnitude.

In upland forests of SE Australia, soils formed in drier landscape positions tend to be more susceptible to degradation [*Laffan et al.*, 1998], and are generally lower in organic matter content, aggregate stability, macro-porosity and infiltration capacity and have a higher bulk density [*Ellis*, 1971; *Langford and O'Shaughnessy*, 1980; *Rees*, 1982; *McIntosh et al.*, 2005; *Sheridan et al.*, 2015]. Variation in soil properties is the result of complex interactions between topography, climate, vegetation and parent material, which has been explored by authors such as *Pelletier et al.* [2013] and *Yetemen et al.* [2015]. Some early post-wildfire research in the south-east Australian region showed erosion rates to be highly variable after wildfire, even within areas in close proximity with similar geology, slope angle and regional climate. For instance, in a study from eastern Victoria, *Chessman* [1986] found that in-stream maximum sediment concentration differed by an order of magnitude between contrasting wetter and drier forests that experienced a similar burn, and attributed this difference to the relatively low infiltration capacity of the soils in the drier forest. In a similar setting *Brown* [1972] noted that hillslopes facing the equator (drier) experienced severe erosion after wildfire, compared to only minor erosion from polar facing (wetter) hillslopes. In these studies suspended sediment concentrations (erosion response) differed between catchments that supported different forest types, however the dominant erosion process was not investigated. *Leitch et al.* [1983] documented a high magnitude post-wildfire "mud-torrent" from steep catchments supporting dry mixed Eucalypt forests, and estimated the erosion from this single event to be 22 t ha^{-1}. More recently, high magnitude post-wildfire erosion events such as debris flows were reported in steep catchments also supporting dry mixed *Eucalyptus* species forest [*Nyman et al.*, 2011; *Nyman et al*, 2015].

These observations of extreme erosion are in contrast to the first year post-wildfire erosion rates measured by *Lane et al.* [2006], from catchments supporting wet *Eucalyptus* species forest of lower aridity. Notably, this intensively studied site produced only interill erosion, despite high fire severity, steep slopes and large storm events [*Lane et al.*, 2006; *Sheridan et al.*, 2007; *Noske et al.*, 2010]. This was attributed high availability of macropores and high rates of hydraulic conductivity in these well structured forest soils, despite the presence of widespread water repellency [*Nyman et al.*, 2010].

The coincidence of high magnitude post-wildfire erosion rates from upland dry forests and the converse in wet forests suggest a possible relationship to soil properties across a dryness gradient. *Sheridan et al.* [2015] used a downscaled aridity index (AI) (dryness index) [*Budyko*, 1974; *Nyman et al.*, 2014b], to classify experimental sites in Victorian upland forests, demonstrating a pronounced (order of magnitude) decrease in post-wildfire hydraulic conductivity with increasing dryness. Variability in post-wildfire physical and hydraulic soil properties were found to be highly correlated with the magnitude of observed post-wildfire erosion [*Sheridan et al.*, 2015]. It was argued that the high runoff generation potential of soils formed in drier upland forested environments could be the key factor driving an erosion process shift from low magnitude rill/interill processes to high magnitude runoff-generated debris flows. In the US steep arid headwater catchments have been identified as an important source of material and runoff for the generation for debris flows post-wildfire [*Cannon et al.*, 2001b; *Cannon et al.*, 2001a; *Gartner et al.*, 2008; *Cannon et al.*, 2010; *Kean et al.*, 2011; *Staley et al.*, 2014], however in Australia these source areas have received limited attention. The upland headwater catchments presented in this study were established at a scale to accurately quantify surface runoff and sediment yield, recovery time and the window of erosion risk from areas prone to producing high post-wildfire sediment yields and debris flows.

Empirical evidence suggests forest soils that have formed in drier environments have the potential to generate substantially more surface runoff after wildfire compared to wetter more productive forests. Higher post-wildfire surface runoff rates are the trigger for large scale erosion and hillslope runoff-generated debris flows [*Cannon et al.*, 2001a]. In addition the post-wildfire recovery time and hence the window of risk for high magnitude erosion events in these more arid areas may be more sustained compared to forested areas in wetter locations. This paper will investigate this in more depth by measuring post-wildfire runoff and sediment loads, as well as soil surface properties over a 5-year period from two small dry forested headwater catchments. . Contrasts in the hydro-geomorphic response after wildfire between locations of different aridity will also be explored.

3. Methods

3.1.Site description

The two study catchments were located within the Stony Gully catchment in the upland country of north-eastern Victoria, Australia, 220 km north-east of Melbourne, -36° 30' 0", 146° 48' 0" (Figure 1). The Köppen-Greiger climate classification for this part of Victoria is Cfa, warm temperate with hot summers and cool wet winters [*Kottek et al.*, 2006]. Aridity index is a measure of long term water balance between net radiation and precipitation [*Nyman et al.*, 2014b] and ranges from 0.2 to 10.2 across Victoria, however in forested upland and alpine bioregions AI ranges from 0.2 to 6.5, with and mean of 2.2. The mean aridity for the small study catchments was 2.2 which is within the range that is typical of many open forests and woodlands in south-east Australia. Dominant tree species in the study catchments were a mix of *Eucalyptus macrorhyncha* and *E. dives*. The understory consisted of a dense cover of low shrubby heath, peas and scattered *Acacia dealbata*, with *Leptospermum multicaule* the dominant understory species present in the catchment facing the equator. The ecological vegetation class (EVC) is Grassy Dry Forest. Geology consisted of sedimentary rock intercalated with finer grained well laminated slate and fine to medium grained sandstone with detrital mica, of low metamorphic grade, part of the Adaminaby group. Soil texture was fine sandy loam/fine sandy clay loam. Stony Gully catchment was selected as it fitted the criteria outlined in *Nyman et al.* [2011] for landscapes susceptible to high magnitude erosion events and debris flows. The whole 209 ha Stony Gully catchment (within which the smaller 0.2-0.3 ha study catchments were located) possessed steep equatorial facing headwater hillslopes (15% of the total catchment has a gradient >30°), supporting dry grass/heathy forest .

<<<<<< Figure 1 >>>>>>

Over an 8 year period from 2002 to 2010, 95% Victoria experienced a prolonged drought with rainfall received being in the lowest 10% of all records [*BoM*, 2010]. In 2009 the catastrophic Black Saturday wildfires burned many locations across Victoria. In north-eastern Victoria the wildfire started 3 km south of the town of Beechworth at 18:00 on 7 February, and burned over 33,000 ha of land including Stony Gully catchment, 9 km north-east of the township of Myrtleford. On that day Wangaratta automatic weather station (AWS) operated by the Australian Government Bureau of Meteorology (BoM), 35 km west of Beechworth measured a maximum temperature of 45.5°C, a relative humidity of 6% and a north-north-westerly wind of 35 km hr^{-1} with gusts up to 57 km hr^{-1}, changing to south-westerly of 20 km hr^{-1} at 23:01 [*Teague et al.*, 2009]. Stony Gully catchment was mostly likely burned around midnight between 7 and 8 February 2009. The wildfire was described as a "fire storm" and extreme [*Teague et al.*, 2009], and completely consumed the canopy of all trees, the understory and removed all surface vegetation and litter. The mean differenced normalised burn ratio (dNBR) for the research catchments was 571.

Long term rainfall records were available at a number of BoM sites which were a variety of distances and directions from Stony Gully, due to the topography of the region some were more suitable in providing a historic rainfall record relative to the study site. The rainfall recorded at the town of Beechworth located 20 km to the north-west provided the longest most continuous record in the region. Another station, Rosewhite at Happy Valley Creek, has been operational since 7 July 2003 and has rainfall records most similar to Stony Gully rainfall (P_S) (Figure 2). Beechworth Composite rainfall (P_B) (Bureau No.: 082001) and Rosewhite rainfall (P_R) at Happy Valley Creek (Bureau No.: 082162) produced strong linear relationships for monthly rainfall data collected during the study, P_S=0.87 P_B (r^2=0.92) and P_S=0.95 P_R (r^2=0.95).

During the 3 years leading up to the Black Saturday wildfires annual rainfall at Beechworth was 19% below average (773 mm). The average combined rainfall for January and February was 101 mm, however during 2009 only 18.4 mm was recorded. Rainfall for the remainder of the year was 737 mm (14%) below average, with the years 2010, 2011 and 2012 being wetter than average (Figure 2). Mean annual minimum and maximum temperatures measured at Beechworth were 7.5 and18.4 °C respectively.

<<<<< Figure 2 >>>>>>>>>>>

3.2. Instrumentation and data collection

Two small convergent headwater catchments either side of a low east west ridge were instrumented on 28 August 2009 to measure overland flow and sediment loads (Figure 3). The areas contributing to the catchments were between 0.2 and 0.3 ha and approximately teardrop in shape, nominally 80 m in length 50 m at the widest point, and each possessed a clear drainage channel. Catchment areas were determined using LIDAR data to produce a 1.5 m resolution digital elevation model (Table 1). These small headwater study catchments were selected to successfully capture the runoff and sediment loads from areas that could contribute to the initiation of, rather than experience, a debris flow.

In each channel a large galvanised metal sediment tray 0.8 m wide × 1.8 m long × 0.28 m deep was embedded so that the top end of the tray was level and centred with the flow of water, and sealed to the channel with cement. The other end of the tray was mounted using posts giving the tray a very slight decline, allowing water to flow from the tray into a 0.8 × 1.6 m manifold which funnelled water through a 0.048 × 0.82m slot into a 0.88 m long tipping bucket (Figure 3b, c, d and e). Metal edging (approximately 2 m in length) was hammered into the ground at an angle parallel to the hillslope flowlines, to capture any flow that was wider than the collection tray. Two baffles (0.18 m high) with holes were installed in each tray to slow flow and allow coarser sediment to deposit. The tipping bucket had a nominal tip volume of 12 L, and was calibrated producing an algorithm relating tip rate to volume per tip. Each tip closed a reed switch triggering an electronic pulse to a Tiny Tag data logger (TGPR-1201, Gemini Data Loggers, UK) which logged at 1 minute intervals, in addition magnetic manual counters were installed. Water and fine suspended sediment was sub-sampled through a splitting device that consisted of a PVC tube 25 mm in diameter with a 115 mm long 2.5 mm wide vertical slot, which was positioned on one side of the tipping bucket collecting a sample of approximately 0.027 L every alternative tip. The sample flowed by gravity through a plastic pipe to 2 200 L plastic suspended sediment tanks, connected at the top to collect any overflow from the first tank, this produced a water sample that was integrated over the time between site services. This methodology and the proficiency of the suspended load sub-sampler has been previously validated by *Sheridan et al.* [2006].

<<<< Figure 3 >>>>>>>

<<<< Table 1 >>>>>>

A tipping bucket rain gauge (TB3/0.2/P, Hydrological Services Pty. Ltd., NSW, Australia) was positioned on the ridgeline between the two adjacent study catchments. Each tip was equivalent to 0.2 mm of rainfall at Stony Gully (P_S) which was logged using a Tiny Tag Logger scanning at a 1 minute intervals. In addition, a HOBO weather station was installed in a clearing on 22 May 2009 approximately 250 m north-west of the catchments. Stony Gully weather station logged rainfall (P_{SW}) using a Hobo data logger (U30-NRC-VOA-10-S100, Onset, USA) and a 0.2mm tipping bucket rain gauge smart sensor (RGB-M002, Onset, USA), data was recorded at 3 minute time steps. Both rain gauges were paired with a manual rain gauge (RG1000, Nylex, Australia) measuring up to 250 mm of rainfall depth in 0.5 mm increments.

Initially sites were serviced after each major rainfall event over approximately 20 mm, and then every 4 to 6 weeks. Servicing involved downloading data loggers and taking manual reading from tipping bucket counters and rain gauges, weighing and sub-sampling the amount of coarse material deposited in the sediment trays, sub-sampling and measuring the depth of water in the suspended sediment tanks. Coarse material was measured by removing the baffles and thoroughly mixing all material that had collected in the sediment tray and manifold using either a shovel and/or paint scrapper. All the material was weighed using a bucket to the nearest 0.02 kg per bucket and two 500 mL representative subsamples were taken for laboratory analysis. This material is referred to as coarse sediment. Water and fine sediment that had collected in the 200 L tanks was sampled by re-suspending all the fine sediment that had collected on the sides and bottom of the tanks, and then taking two 500 mL representative samples for analysis. Data are therefore broken up into service intervals, with 67 services occurring during the monitoring period averaging 24 days between visits. The dry mass of coarse sediment was determined by drying one of the samples in the oven at 105°C until a stable mass was obtained. The other sample was air dried and stored for further analysis. The concentration of fine sediment was determined in duplicate by transferring a known volume to a 30 mL glass vial, and drying at 105°C and weighing remaining sediment.

3.3.Data analysis

Rainfall events that produced surface runoff at the catchment outlet were identified as individual storm events. Storm events were defined as the start of rainfall (a tip from the rain gauge) that produced runoff (a tip from the runoff tipping bucket) within 60 minutes, until runoff had ceased by 60 minutes (60 min time window). The length (min), total rainfall (mm), total runoff, maximum 15 minute rainfall intensity (I_{15}), maximum 15 minute discharge, time delay between the start of rainfall and the peak in runoff, and the runoff recession time from the peak in runoff were calculated for each storm event. From this method an average of 384 discreet storm events occurred in each catchment. A measure of erodibilty was calculated for each service interval, by dividing the total sediment load by maximum 15 minute discharge rate (L s^{-1}).

Ratio of runoff to rainfall or runoff coefficient (RC) was calculated

$$RC = \frac{\sum Q}{\sum P} \quad (1)$$

Where Q is total runoff (mm) and P total rainfall (mm) measured during given period of time i.e. storm event or field site service interval. The Wilcoxon signed rank test [*Wilcoxon*, 1945] was used on matched pairs (i.e. polar and equatorial) to test if there was a significant difference between calculated service interval RC, storm RC, start of runoff and recession times, for each year of monitoring.

3.4. Pre-installation measurements

Monitoring of the sites began 200 days after the wildfire, therefore it was necessary to estimate the amount of runoff and erosion that occurred before the equipment was installed. Rainfall data from a tipping bucket rain gauge located at nearby Rosewhite was used as a proxy between 8 February 2009 and 22 May 2009, and from Stony Gully weather station between 23 May 2009 and 28 August 2009. A strong linear relationship for daily rainfall existed between Rosewhite and Stony Gully, P_S=0.95P_R-0.03 (r^2=0.90). Instantaneous rainfall data was divided into discrete storm events. Rainfall data (Ps) from the first 12 months of monitoring was grouped in 1mm increments from 0 to 5mm (e.g. <1mm, 1-2mm), then 5 mm increments from >5 to 20 mm (e.g. >5-10mm) and finally >20mm, total rainfall for events in each increment was averaged and plotted against the average storm event RC for that increment. The relationships for the catchments (Figure 4) were then used to calculate runoff for each storm event that occurred prior to the equipment being installed, using P_R and P_{SW}. Sediment loads from each catchment were also estimated using the average sediment concentration measured during the first year after wildfire (5 months of data).

<<<<< Figure 4 >>>>>>>>>

3.5. *Estimation of missing data*

During one storm event discharge measurements were disrupted by debris stopping the tipping buckets at both catchment. Runoff was estimated using the relationship between total rainfall and RC from individual storm events 1.5 months pre- and post-blockage. The relationships in the equatorial and polar facing catchments were RC=0.13 ln (P_S) – 0.12 (r^2=0.81) and RC=0.093 ln (P_S) – 0.1 (r^2=0.90) respectively. Calculated RC was then used to estimate runoff.

When there was disruption to runoff measurements at one catchment, the RC relationship between the catchments was used to estimate runoff. During the five year study, 1 storm event in the equatorial facing catchment and 8 in polar facing catchment were disrupted. A relationship between the RC measurements from each catchment was plotted for storm events > 5 mm, 2 months either side of the date interruption, the linear relationships produced r^2 values ranging from 0.93 to 0.72.

3.6. *Soil surface and vegetation measurements*

Measurements of soil hydraulic conductivity, water repellency and surface cover were conducted approximately 6, 12 and 18 months and 5 years after the wildfire, on 17 September 2009, 25 March 2010, 30 September 2010 and 25 March 2014. Soil hydraulic conductivity and water repellency measurements were made on the ridge, mid-slope and 2m from the channel edge, in each catchment on each flank, 30 and 60 m upslope from the sediment tray. Tension infiltration measurements were completed in duplicate at each location using a Decagon mini-disk infiltrometer (Decagon Devices, Inc., 2007). Tension was set at 2 cm reducing the effect of large macropore flow and allowing soil pores up to 1.45 mm in diameter to fill. Tests were located nearest to the point that had a level area that was 4 cm in diameter, avoiding rocks, trees and large holes. A thin smear of petroleum jelly was applied to the inside of a metal cylinder 53 mm in diameter which was inserted approximately 10 mm into the soil surface. The infiltrometer was held upright and in place by a metal pin and clamp, and the test was concluded when either the infiltration rate had reached steady state or there was no infiltration after several minutes. Immediately after this, a measure of matrix and macropore flow was made in duplicate using a 50 mm diameter disk permeameter manufactured to the design of *Perroux and White* [1988], which supplied water at a positive pressure with a head of 5 mm.

Water repellency measurements were completed using the method described by *McDonald and Isbell* [2009], which involved measuring the time for distilled water and 2M ethanol to be absorbed into the soil. The tests were located near the infiltrometer experiments using 5 drops of solution on the surface (0 cm) and at 1 cm depth. Soil samples were also collected in air tight containers at each location at depths of 0-2 and 2-4 cm for obtaining gravimetric water content (GWC) for each campaign. The percentage vegetation (including mosses) and litter (leaves and branches) cover were estimated visually using field cover charts produced by *McDonald et al.* [2009]. This was completed along transects starting at intervals of 0, 20, 40 and 60 m from the top of each sediment tray along the channels at each site. Transects extended from the drainage line to the ridgeline with measurements made using a square 1m by 1m quadrat at 10 m intervals. An additional estimate of vegetation surface cover was also made on 5 July 2013. Wilcoxon rank sum test [*Wilcoxon*, 1945] was used to compare measurements made between catchments for surface cover, infiltration and GMC. Photo points were also established at the base of each catchment to the left of the sampling equipment. Photographs were taken periodically to capture an image of vegetation recovery over time.

3.7. Soil sampling

Soils were sampled mid-way between the ridge and the channel on each flank of the catchments. Catchments were split into quarters with sample locations at the base and within each quarter, with one sample taken at the dividing ridge. Soil samples were collected at 0-3 and 3-7.5 cm depth, and an intact soil core 73 mm in diameter and 77 mm in height was also collected for bulk density determination. Bulk density samples were dried in an oven at 105°C and weighed. Other samples were air dried, sieved to 2 mm and the soil texture determined using the Field Texture method detailed in *McDonald and Isbell* [2009]. Soil colour was determined using Munsell Soil Colour Charts [*Munsell*, 1975].

4. Results

4.1. Runoff and Sediment Loads

Rainfall and surface runoff data were separated into service intervals to match the coarse and fine sediment collection dates. Results from each service interval were then combined into years and are presented in Table 2. The first year of data is a combination of measured and predicted, for the following years all the data were measured. RC, sediment concentration and total sediment load generally decreased throughout the 5 year monitoring period (Table 2 and Figure 5).

<<<<<<< Table 2 >>>>>>>>>>

Rainfall in north-eastern Victoria generally peaks in winter and reduces during summer and autumn. However during the summer of 2011 rainfall was 3 times higher than the average measured at Rosewhite (since 2003). Rainfall intensity oscillates seasonally, with 15-minute maximum rainfall intensity (I_{15}) peaking around summer each year (Figure 5b), which coincided with increases in the RC and sediment loads. Two high peaks in average RC occurred during the first two summers, after which RC generally reduced with time, even though the annual rainfall measured during the first 3 years of the study was higher than the average annual rainfall and high intensity storms occurred each year. The data presented in Figure 5c shows that the average RC peaked at 0.45 at the start of monitoring before reducing to below 0.10 by 2013. Average cumulative runoff (Figure 5d) produced 3 distinct gradients with runoff remaining relatively constant from the time of wildfire to winter 2010 (July 2010), increasing during the wet period up until summer/autumn 2011, until the average RC fell below 0.15 then the gradient remains fairly constant until the end of the study (Figure 5). After summer/autumn 2011 the RC continued to decline, with the exception of two outlying values recorded during high intensity events during the following summers, which corresponded with increased surface runoff totals.

During the first year after wildfire average sediment concentration (5-6 months of measurements) was more than double the second year concentration (Table 2). The average mass of coarse sediment was also greater during the first year in comparison to the second year, even though the monitoring time was shorter. The average mass of fine sediment exported peaked during the wetter than average second year, and remained higher than coarse sediment during the remainder of the study. From the installation of monitoring equipment August 2009 until January 2010 average cumulative sediment yield increased at a constant rate (Figure 5d) before a sharp increase produced by the high intensity summer storm events. Rates of erosion then reduced before another rise in summer 2010-11, again coinciding with high rainfall intensity but also high rainfall totals, before plateauing for the remainder of the study. Maximum 15 minute storm intensity continued to peak each summer however the increase in sediment generation is muted during the third and fourth years post-wildfire and hardly noticeable by the fifth year (Figure 5d). Total sediment yield averaged 18.8 t ha^{-1} between the two catchments over the 5 years of monitoring (including estimated yield before equipment installation). Average fine and coarse sediment yields were similar up until July 2010, 1.5 years after wildfire, then over the next 6 months the amount of coarse being exported reduced considerably, while fine sediments continued to be exported at a rate similar to the first 6 months of monitoring. After February 2011 the export of both sediment types declined.

<<<<< Figure 5 >>>>>>>>>

4.2.Soil surface measurements

The soil surface (0 cm) was non-repellent (wettable) throughout the study, while at 1 cm depth repellency was detected at between 70 to 88% of all locations during the first 3 field campaigns (Table 3). The average surface cover of litter and low vegetation generally increased during the study (Table 3). The lowest detectible rate of infiltration using the methods in this study was 2 mm hr^{-1}, for that reason all zero values were converted to this lower threshold. Infiltration data had a lognormal distribution, means and coefficients of variation were calculated from the data using the method detailed by *Mallants et al.* 1996 (Table 4). The number of locations producing undetectable rates of infiltration reduced from 57% to 3% and from 98% to 12% for tension and ponded conditions, between the first and last date of measurements respectively. The final campaign at the end of the study was the only occasion when more than 50% of locations across the catchments were non-repellent and average steady-state infiltration had increased to similar maximum rates previously measured

<<< Table 3 >>>>>>

<<< Table 4>>>>>>

4.3.The influence of aspect

The equatorial facing catchment is 19% larger than the polar facing catchment, however the general catchment shape and slope are similar (Table 1). Although the aspects differed, the average aridity index only differed by a small amount (Table 1). Soil texture, colour and bulk density were similar between catchments. Measurements from the two catchments are presented in Figure 6. Note that modelled data used in the previous section to predict runoff and sediment loads prior to equipment installation has been excluded from this figure. During the first year after wildfire the amount of runoff was similar for both catchments, however during years 2 and 3 the amounts measured diverged as the catchments recovered (Figure 6a). At the end of monitoring total runoff from the polar facing catchment was 1/3 lower than the equatorial facing catchment, producing 606 mm compared to 906 mm. After the initial 3 years the cumulative rate of runoff being produced from both catchments remained relatively consistent, with a higher amount from the equatorial facing catchment.

Measured sediment concentrations and yields were also similar for both catchments during the first year post-wildfire, with large differences occurring during the second year (Figure 6b and c). The equatorial facing catchment produced more sediment than the polar facing during second year after wildfire, after which sediment yields were lower from both catchments. By the end of the study the measured (not including estimated) amount of sediment produced from the equatorial facing catchment was almost double the sediment from the polar facing catchment (18.8 and 9.7 t ha^{-1} respectively), with most of this divergence occurring during the second year. Sediment yields measured during the first year after wildfire for the equatorial and polar facing catchments were similar at 2.8 and 2.1 t ha^{-1} for fine sediment and 3.4 and 2.6 t ha^{-1} for coarse sediment, respectively (fine and coarse sediment loads were not estimated for the period before equipment installation). During the second year fine yields were 7.2 and 2.3 t ha^{-1} and coarse yields were 3.1 and 1.4 t ha^{-1}, for the equatorial and polar facing respectively after which erosion rates plateaued. There was significantly more litter cover in the polar facing catchment during final measurements (26 March 2014), indicating a higher rate of litter accumulation. Surface vegetation cover only differed significantly between catchments during the second measurement, however mean cover was similar throughout the study. Note that the low vegetation measurements do not quantify the substantial observed differences in mid and overstory vegetation recovery. The times series photographs presented in Figure 7 show that the polar facing catchment became revegetated at a faster rate than the equatorial facing catchment. In the polar facing catchment by the summer 2010, sediment yields had reduced, particularly the coarser fraction (Figure 6), and vegetation cover had clearly increased (Figure 7).

<<<<<< Figure 6 >>>>>>>>>>>>>

<<<<<< Figure 7 >>>>>>>>>

A measure of effective erodibility was obtained by dividing the total sediment load between servicing intervals by the peak 15-minute discharge in that same period (Figure 8). The equatorial catchment produced more sediment (more erodible) during large storm events up until the wet summer 2010/11, after which erodibility clearly reduced in both catchments, particularly the equatorial facing. After this wet period some larger storm events produced minor rises in erodibilty and sediment yield particularly in the polar facing catchment, however sediment yields from these later service intervals were low relative to earlier measurements (Figure 8).

<<<<< Figure 8 >>>>>>>>>

The average annual RC, and RC calculated for storm events >20 mm h^{-1} reduced with time since the wildfire in both catchments, and was lower in the polar facing catchment throughout the study (Table 5). Average annual RC per service interval differed significantly between the two catchments from year 2, with the equatorial facing catchment generally producing more runoff with rainfall. Average annual storm event RCs differed significantly in years 1 and 4, however average values remained lower in the polar facing catchment, indicating less rainfall was being converted to surface runoff during larger rainfall events. .

<<<<< Table 5 >>>>>>>>>>

A total of 59 discreet storm events were identified and used to investigate i) the time delay between the start of rainfall and the start of runoff, and ii) the duration of runoff recession flow from the final peak in the storm hydrograph to the final tip of the runoff tipping bucket. A longer time delay in the detection of runoff from the start of a rainfall event, and median recession flow time, was found in the polar facing catchment during the second and subsequent years (Table 6).

<<<<<<<< Table 6 >>>>>>>>

Measurements of soil water repellency during the two years after wildfire indicated that the equatorial facing catchment was more repellent than the polar facing catchment, however by 2014 repellency had reduced to equally low levels (Table 3). The gravimetric water content means were marginally wetter in the polar facing catchment, except for the 0-2 cm samples collected on the 17 September 2009 which were affected by a rainstorm. Steady state infiltrations measurements were generally low in both catchments during monitoring (Table 4). ean rates for infiltration under tension varied between 5.8-22.3 and 2.8-16.8 mm h^{-1} while ponded rates ranged from 2.1–44.2 and 2.8–24.7 mm h^{-1} for the equatorial and polar facing catchments respectively. Infiltration rates though low, were significantly higher in the polar facing catchment at the end of winter 2009 (23 March 2010) compared to the equatorial facing catchment, using tension infiltrometers ($p<0.05$). No statistically significant difference was found using the ponded infiltrometer. It is unclear why the ponded infiltration experiments in 2009 yielded lower rates than infiltration under tension. Results do show that macroporisity in these soils are low.

5. Discussion

5.1.Surface runoff and soil properties after wildfire

Surface runoff ratios from these experimental catchments were very high, averaging 0.30 in the 2 years following wildfire, and even higher for individual storm events (I_{15}>20 mm h^{-1}) averaging 0.45 in the first year after wildfire. Throughout this study annual rainfall gradually reduced from 2010 but remained above the long term average at Beechworth BoM site until 2012. There were significant high intensity storm events each year throughout the 5 years of monitoring (Figure 5), with the average storm RC continuing to decline as the catchments recovered (Table 5). The soil surface measurements in this study indicate that the high runoff ratios observed (up to 0.45) are associated with extremely low mean field saturated hydraulic conductivity. Detectable infiltration rates in this forest soil were comparable but low relative to studies conducted in similar dry forest types by *Nyman et al.* [2011] and *Nyman et al.* [2014a], with mean steady state ponded infiltration rates ranging from 2.1 to 44.2 mm hr^{-1}. Over the 5 years of monitoring at Stony Gully the incidence of zero infiltration and water repellency did decline and soil moisture increased (not including samples taken on the 17 September 2009). We postulate that small changes in water repellency and infiltration, coupled with vegetation regrowth and litter accumulation may have combined to reduce the RC during monitoring.

Water repellency is commonly reported in Eucalypt forests before and after wildfire [C*rockford et al.*, 1991; *Shakesby et al*., 2003; *Doerr et al*., 2004], however it does not always result in conditions conducive to increased surface runoff rates. In well-structured soils for instance, *Oono* [2010] measured soil water repellency and hydraulic conductivity in unburned and wildfire burned hillslopes and found that despite test locations being 8% to 90% water repellent respectively, the difference in mean hydraulic conductivity between sites was small (626 mm h^{-1} in unburned soil and 434 mm h^{-1} in burned soil) . These results, alongside those of *Sheridan et al.*, [2007] and *Nyman et al.* [2010], show that if soils are well structured (e.g. bulk density of < 0.8 g cm^{-3}), then infiltration can remain high despite widespread wildfire-enhanced water repellency, reducing the likelihood of overland flow. However if soils lack structure, as is the case in this study (e.g. bulk density of 1.4 g cm^{-3}), then increases in water repellency following wildfire can result in large increases in surface runoff.

5.2.Sediment erosion

The experimental catchments were established in an area with an average aridity index of 2.2 which is typical of many open forests and woodlands in Victoria, Australia, within which numerous post-wildfire debris flows were observed by *Nyman et al.* [2011] and *Nyman et al.* [2015]. The decline in surface runoff ratios (average and storm) measured at Stony Gully suggests initially that the window of risk for high sediment yields and debris flows could be 4 years. However despite these elevated runoff ratios, the sediment yield declined abruptly and substantially (by approximately 1 order of magnitude) after year 2 to approximately background levels (Figure 8). This suggests that after 2 years of erosion any further erosion was primarily limited by sediment supply on the hillslope, and not the transport capacity of the runoff. This observation is supported by the dramatic reduction in the measure of erodibilty in both catchments after the exceedingly wet summer 2010/2011 (Figure 8). These findings are consistent with *Nyman et al.* [2013] who found that after wildfire in drier forested areas there is a finite amount of non-cohesive material available on the soil surface for transport, and this material declined exponentially to background levels after approximately two years. In terms of hillslope erosion rates, the two year recovery time is longer than that reported for the wetter East Kiewa site where the sediment yield diminished sharply within 8 months of the wildfire [*Lane et al.*, 2006; *Sheridan et al.*, 2007; *Lane et al.*, 2012]. The drier than average year after the wildfire in 2009 may have delayed the recovery of vegetation at Stony Gully, making the catchments more susceptible to erosion during the large summer storms that occurred in 2010/2011. This scenario is not unique, with storms and subsequent large erosion events frequently documented after wildfire [*Nyman et al.*, 2011, 2015], with the average annual maximum rainfall intensity (I_{15}) for the region ranging from 30 to 50 mm h^{-1} [*Nyman et al.*, 2015]. The 2-year reduction in sediment yield from this dry *Eucalyptus* forest matches the time for runoff generated debris flow susceptibility in the western USA given by *Cannon and Gartner* [2005] and for coarse sediment movement measured by *Wagenbrenner et al.* [2006], but is shorter than the hillslope erosion recovery reported by *Moody and Martin* [2001] of 3-4 years.

Average total sediment yields were 10 and 7 t ha^{-1} in the first and second year, reducing to 0.1 t ha^{-1} in the final (fifth) year of the study. Soil loss from undisturbed forests and uncultivated pastures in Victoria and New South Wales have been estimated at 0.65 and 0.45 t ha^{-1} y^{-1} respectively [*Loughran et al.*, 2004], and modelled at 0.56 t ha^{-1} y^{-1} for forested areas of the Murray Darling Basin [*Lu et al.*, 2003]. Erosion rates from undisturbed wet forests were measured to be 0.23 t ha^{-1} y^{-1} [*Papworth et al.*, 1990; *Lane et al.*, 2006] and relatively unburned (7% burned in the headwaters) catchments were estimated to produce 0.52 t ha^{-1} y^{-1} [*Chessman*, 1986]. These results are broadly consistent with the experimental data from this study (year 5) and indicate sediment loads from these unburned more arid forests is generally <0.5 t ha^{-1} y^{-1}.

Comparisons with other post-wildfire studies from similar forest types are difficult because of differences in experimental methods, particularly plot studies with the inherent scaling uncertainties. However, the high resolution results from this study broadly confirm the comparatively high hillslope erosion rates measured in other post-fire studies. *Blong et al.* [1982] measured rates between 2.5 and 8.2 t ha^{-1} yr^{-1} after a moderate wildfire in sandstone geology with less than average annual rainfall, but suggested the real rate could be closer to 20 t ha^{-1} y^{-1} under average rainfall conditions. *Atkinson* [2012] measured sediment yields between 40 and 64 t ha^{-1} yr^{-1} which included three very large rainfall events. By years 4 and 5 erosion rates had fallen to 0.62 t ha^{-1} yr^{-1} a rate similar to year 3 of this study. *Chessman* [1986] estimated post-wildfire sediment yields from in-stream grab sampling of 4.5 t ha^{-1} yr^{-1} from catchments of dry sclerophyll forest with hard setting duplex soils. In contrast, large rainfall simulation experiments (300-450 m^2) designed to test the effectiveness of burnt filter strips in sediment removal after logging were conducted in wet eucalypt forests (AI ≈ 1.3), during high intensity rainfall minimal runoff and sediment generation was measured [*Lane et al.*, 2004].

The data indicate that in upland dry eucalypt forests when only rill and interill processes are active (no debris flows), annual sediment exports would increase approximately 100- fold after wildfire, and that this increase lasts for approximately 2 years depending on rainfall. Put another way, high severity wildfire in a dry forested upland area results in the equivalent of approximately 200 years of erosion from unburned forested hillslopes. However, these increases in hillslope erosion do not include the potential contribution of post-wildfire debris flows, which have been shown to produce erosion rates >100 t ha^{-1} [*Nyman et al.*, 2011; *Nyman et al.*, 2013; *Nyman et al.*, 2015], resulting in a 1000-fold increase in sediment load over background levels.

5.3. Regional effects of aridity – comparison with wet forests

The results in this study differ dramatically from those reported for wetter *Eucalyptus* forests from nearby East Kiewa research catchments (mean AI of 1.4) by *Lane et al.* [2006], *Sheridan et al.* [2007], *Nyman et al.* [2010] and *Lane et al.* [2012] following the intense wildfire of 2003. These authors used infiltration measurements, rainfall simulation, field observations, flow measurements and analysed catchment flow duration curves and found no evidence of broad scale infiltration excess surface runoff from the burned hillslopes. Considering the different post-wildfire hydrological processes operating in these different forest types, indirect measurements of hydraulic conductivity, water repellency and surface cover during recovery are presented to illustrate how forested hillslopes and catchments of different AI respond to wildfire (Table 7).

Storm flow events from these catchments (from *Sheridan et al.* [2011]) were used to calculate RC from the East Kiewa catchments as the creeks were perennial. As expected the RC calculated was low (range 0.02 – 0.03) in comparison to Stony Gully (range 0.27 – 0.05), as the hydraulic conductivity remained high (>333 mm hr^{-1}) even after the intense wildfire (Table 7). Recent research has highlighted the importance of intrinsic soil properties such as bulk density, porosity and gravel content in post-wildfire erosion response, which differed considerably between these two study sites. *Sheridan et al.* [2015], for instance, hypothesised aridity as a control on forest soil infiltration properties and the subsequent erosion response after wildfire. Although infiltration was measured using different techniques, the contrast between the two sites was clear (Table 7). In addition to inherent site differences in hydraulic conductivity there are factors associated with moisture availability that promote faster recovery in wet environments. For instance, water repellency reduced and surface cover increased at a faster rate during post-wildfire recovery at the East Kiewa site compared to Stony Gully.

These pronounced differences in intrinsic soil properties and recovery trajectories provide a plausible explanation for why 14 of the 15 post-fire debris flows investigated in south-east Australia by *Nyman et al.* [2011] occurred in dry *Eucalyptus* forests. These 14 debris flows were all identified as being runoff-generated (in contrast to slip failures), and therefore dependent on the generation of sufficient hillslope surface runoff to trigger debris flows. It should be noted that while the slopes in Stony Gully experimental catchments are not steep or long enough to generate debris flows, storm events in early 2011 coincided with 3 debris flows in the greater Stony Gully catchment, 15% of which has a slope ≥30°. In contrast, the absence of any runoff generated debris flows in low aridity forests is consistent with the minimal surface runoff observed from wetter forests in the aforementioned studies.

<<<<<<Table 7>>>>>>

5.4. Local effects of aridity – aspect-related differences

Despite being very similar in terms of size, shape, relief, geology, soils, vegetation, land use history, and aridity index (2.3 on equatorial vs 2.0 on polar), the two catchments in this study differed markedly in terms of post-wildfire runoff and erosion response. The sediment totals from equatorial facing catchment after 5 years was approximately double that of polar facing catchment (ca 24 vs 13 t ha^{-1}). Much of this difference in yield can be explained by large differences in fine sediment concentrations between the polar and equatorial facing catchments that occurred during the first and second summers after the wildfire (Figure 6 a, b, c). Both before and after these summers sediment concentrations from the two catchments were similar.

Identifying the cause of these short term, yet significant catchment differences is difficult. Near-surface vegetation cover was averaged across each catchment and found to be similar during each measurement campaign. From field observations the polar facing catchment soil surface had more cover from mosses, herbs, small shrubs and from resprouting eucalypts and the equatorial facing more spreading shrubs (Figure 7). Litter accumulated at a greater rate in the polar facing catchment. Initially this catchment contained more fallen branches from larger trees and over time more leaf material, however in the second year of the study these differences in litter were small. The analysis of individual storms during the second year (Table 5) indicates similar mean storm runoff ratios between 0.33-0.34, however hydrograph analysis (Table 6) for the same year indicates a significantly longer time to peak runoff, and a median runoff recession more than two times longer in the polar facing catchment. Vegetation regrowth and the accumulation of litter increases rainfall interception and storage [*Crockford and Richardson*, 2000; *Ebel*, 2013] and increases surface roughness which enhances infiltration by slowing overland flow and creating more areas for surface ponding [*Dunne et al.*, 1991; *Lavee et al.*, 1995; *Zierholz et al.*, 1995]. It is possible that in these critical summer periods in the second year, when rainfall intensities were at their greatest (Figure 5b), hydraulic conductivities were low (Table 4), the water interception and holding capacity of the additional vegetation, the presence of more woody debris litter and mosses in the polar facing catchment may have smoothed the hydrograph and reduced peak flows to a sufficient degree to limit erosion. This assumption is supported by the lower erodibility initially measured in the polar catchment (Figure 8) which may have resulted from the initial presence of more woody debris, and/or a threshold of erodibility being overcome in the equatorial facing catchment when higher peak flows were experienced. Change in erodibility was more abrupt in the equatorial facing catchment, indicating a limitation in sediment supply after the wet summer of 2010/2011. The decreased erodibility and sediment yield generally continued throughout for the remainder of monitoring, even though there were many service intervals that experienced high peak discharge. A more gradual reduction in erodibility was measured in the polar facing catchment, and this may indicate some limitation through the trapping of material. It is postulated that the small rises later in the experiment was the result of trapped material being released during large storm events. Between the two catchments there was also a difference in the amount of coarse material transported in the second year, indicating a lower transport capacity of the overland flow and/or sediment trapping in the polar facing catchment (Figure 6).

Over time the surface, understory and canopy cover increased at a higher rate in the polar facing catchment (Figure 7) which would reduce rain-splash energy [*Shakesby et al.*, 1993; *Benavides-Solorio and MacDonald*, 2001; *Johansen et al.*, 2001; *Pierson et al.*, 2002], dissipate erosive energy of overland flow [*Pierson et al.*, 2002; *Pierson et al.*, 2008; *Pierson et al.*, 2009; *Stoof et* *al.*, 2015] and trap material [*Pierson et al.*, 2002; *Pierson et al.*, 2009], all of which would reduce sediment export. *Pierson et al.* [2002] attributed the variation in post-fire erosion with aspect to the effect of vegetation and litter on storage surface roughness. Forested areas in Mediterranean climates in Israel [*Wittenberg et al.*, 2014] and Spain [*Marqués and Mora*, 1992; *Andreu et al.*, 2001] have also produced different erosion responses with aspect. *Andreu et al.* [2001] found polar facing plots to produce lower sediment yields, to be more resistance to erosion and to have higher aggregate stability, yet the runoff coefficients did not vary with aspect. While the influence of aspect and forest type (reflected in the AI) on post-wildfire runoff and erosion from Australian forests has been noted previously (eg. *Brown* [1972] and *Chessman* [1986]), this study highlights the extreme sensitivity of erosion processes to even slight differences in aridity. The influence of radiation distribution on the regulation of vegetation and consequent hydrologic and geomorphic fluxes has been long recognised. The review paper of *Wondzell and King* [2003] highlighted the greater potential for severe erosion in drier inland mountain areas compared with the wetter Pacific north-west in the US. More recently it has been argued radiation distribution may even be a key driver of landscape evolution [*Yetemen et al.*, 2015]. Even the small difference in aridity between the equatorial and the polar facing Stony Gully catchments resulted in substantial differences in post-wildfire surface runoff and erosion. This result adds further support to the argument that forested upland landscapes with a higher AI in this region have the potential to produce more surface runoff and are more prone to larger erosion events after wildfire.

6. Conclusion

Surface runoff and erosion from two small dry forested catchments after a severe wildfire were measured in conjunction with the measurement of soil surface properties. High rates of surface runoff were produced during storm events I_{15}>20 mm h^{-1} in the first year post-wildfire with average runoff to rainfall ratios greater than 0.4. Rates remained high for 4 years after wildfire. Infiltration remained low throughout the study, and was deemed to be an inherent characteristic of this site (and maybe other dry forested hillslopes) considering only a small change was detected 5 years after wildfire. Over time surface runoff ratios decline but remained elevated for 4 years after wildfire, indicating that dry forested hillslopes may remain susceptible to high magnitude erosion for this time, depending on rainfall patterns and the availability of sediment. Total sediment loads eroded were of similar magnitude to plots studies in burned native forests in Australia. Sediment yield and erodibility declined substantially after a very wet period in the second year. This decline was abrupt in the equatorial facing catchment, indicating an exhaustion of sediment available for transport. This result suggests that the window of risk for high magnitude erosion events on dry forested hillslopes might be constrained by the availability of sediment after periods of high rainfall, i.e. 2 years for this study.

These results contrast dramatically from those of other studies in burned wetter forests of lower AI. Ponded infiltration rates measured in the East Kiewa study were significantly higher, surface cover increased and water repellency decreased at a faster rate, and low average annual runoff ratios for storm flow were measured from year 1 post-fire. These data indicate that more surface runoff and erosion occurs from forested areas in drier more arid locations (holding other factors constant) after high intensity wildfires. This is supported in the significantly different results in runoff and annual sediment loads between the equatorial and polar facing catchments in this study.

Wildfire results in erosion rates from these drier upland forests that are 100 times greater than background rates when only interill and rill processes are active, and 1000 times greater when debris flow processes are active [*Nyman et al.*, 2015]. The high conversion rate of rainfall to surface runoff in these dry eucalypt forests upland areas is thought to be the main driver for high magnitude erosion events. Therefore, dry eucalypt forests such as those in Stony Gully are much more likely to experience a step-change in erosion process from lower magnitude rill and interill processes (10 t ha^{-1}), to high magnitude (100s t ha^{-1}) runoff generated debris flows in steep terrain.

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8. Tables

Table 1 Characteristics of two small catchments in Stony Gully catchment

Catchment	Equatorial facing	Polar facing
Size (ha)	0.32	0.26
Length, Width (m)	81,52	79,46
Average slope from catchment outlet to ridge along channel (degrees)	13.2	13.4
Aspect of hillslopes (%)	North 29 North-east 32 North-west 38 Other 1	South 24 South-west 59 West 13 Other 4
AI value	2.3	2.0
Net radiation (MJ m^{-2} y^{-1})	5575	5157
Soil texture		
0-3 cm	Fine sandy loam	Fine sandy loam/Fine sandy clay loam
3-7.5 cm	Fine sandy loam/Fine sandy clay loam	Fine sandy clay loam
Colour		
0-3 cm	Hue 10YR, brown/dark brown	Hue 10YR, brown/yellowish brown
3-7.5 cm	Hue 10YR, yellowish brown/dark yellowish brown	Hue 10YR, yellowish brown
Bulk density (g cm^{-3})	1.41	1.38

Table 2 Average data for equatorial and polar-facing catchments arranged by year after wildfire

	Year since wildfire				
	1 (2009-2010)	2 (2010-2011)	3 (2011-2012)	4 (2012-2013)	5 (2013-2014)
Start Date	8/02/09	9/02/10	10/02/11	7/2/12	21/2/13
End Date	9/02/10	10/02/11	7/02/12	21/2/13	12/2/14
Rainfall (mm)	672[a]	1387	881	876	824
Surface runoff (mm)	183 (37)[b] [208, 158][b]	361 (59) [403, 320]	127 (52) [164, 90]	124 (47) [157, 90]	42 (36) [68, 17]
Annual RC	0.27 (0.05)[b]	0.26 (0.04)	0.14 (0.06)	0.14 (0.05)	0.05 (0.04)
RC, for storm events I_{15}>20 (mm h^{-1})	0.45 (0.04)	0.33 (0.10)	0.28 (0.04)	0.22 (0.07)	0.12 (0.05)
Sediment concentration (g L^{-1})	4.8 (0.04)[c]	2.1 (0.92)	0.47 (0.03)	0.49 (0.15)	0.25 (0.15)
Coarse sediment load (kg)	882 (308)[c]	676 (446)	49 (46)	69 (21)	19 (23)
Fine sediment load (kg)	721 (243)[c]	1451 (1212)	202 (115)	155 (33)	21 (24)
Total sediment yield (t ha^{-1})	10.1 (2.2)[b] [11.6, 8.5][b]	7.0 (4.68) [10.3, 3.7]	0.8 (0.43) [1.1, 0.5]	0.8 (0.07) [0.8, 0.7]	0.1 (0.14) [0.2, 0.03]

Standard deviation in parenthesis

[a] Rainfall measured at Rosewhite 8/02/09–15/05/09 and Stony Gully weather station 15/05/09–28/08/09

[b] Estimated from time of wildfire (8/02/2009) until equipment installation (28/08/2009) then measured until 9/02/2010

[c] Measured from the 28/08/2009 till the 9/02/2010

Square brackets surface runoff and sediment yield data each study catchments, equatorial facing catchment, polar facing catchment

Table 3 Equatorial and polar-facing catchments, soil and vegetation measurements

	Water repellency at 1 cm depth (%)			Mean GWC (%)		Mean surface cover (%)	
Date	Strongly repellent	Repellent	Non-repellent	0-2 cm depth	2-4 cm depth	Low vegetation	Litter
17/09/09	74 [100, 46]	4 [0, 9]	22 [0, 46]	13 (8) [14 ,13]	9 (5) [5, 13]	0.4 (1.4) [0.3, 0.5]	2.1 (4.5) [1.0, 3.2]
23/03/10	59 [64, 54]	11 [14, 8]	30 [21, 39]	2 (1) [2, 3]	3 (1) [2, 3]	11.6 (12.3) [12.1, 11.1]	3.4 (6.0) [3.5, 3.4]
30/09/10	84 [92, 75]	4 [8, 0]	12 [0, 25]	4 (2) [3, 5]	7 (4) [5, 9]	19.2 (17.9) [17.9, 20.8]	4.3 (9.8) [3.5,5.3]
5/07/12	-	-	-	-	-	47.4 (22.0) [48.3, 46.7]	13.3 (13.7) [10.4, 16.0]
26/03/14	33 [25, 42]	13 [17, 8]	54 [58, 50]	11 (5) [8, 15]	8 (2) [6, 9]	34.7 (19.0) [32.3, 37.2]	19.8 (17.0) [12.7, 27.2]

GWC, is the gravimetric water content of the soil at the depth indicated
In parenthesis, standard deviation for all measurements in both catchments
Square brackets, average of measurements made, equatorial facing catchment, polar facing catchment

Table 4 Mean hydraulic conductivity for combined and individual catchments

Date	Tension			Ponded		
	All	Equator	Polar	All	Equator	Polar
17/09/09	4.2 (76)	2.9 (45)	5.8 (93)	2.5 (43)	2.8 (63)	2.1 (0)
23/03/10	18.1 (165)	14.7 (155)	22.3 (174)	29.4 (374)	19.4 (311)	44.2(444)
30/09/10	6.9 (95)	8.4 (114)	5.6 (77)	6.5 (127)	6.0 (118)	7.2 (141)
26/03/14	12.1 (112)	16.8 (139)	8.7 (83)	22.3 (200)	24.7 (213)	21.1 (202)

In parenthesis, coefficient of variation (%).

Table 5 Catchment average annual runoff ratio

	Average service interval RC		Average storms I_{15}>20 mm h^{-1} RC	
Year since wildfire	Equatorial facing	Polar facing	Equatorial facing	Polar facing
1	0.30 (0.13, 12)	0.23 (0.14, 12)	0.46 (0.05, 4)	0.43 (0.04, 4)*
2	0.28 (0.09, 22)	0.21 (0.09, 22)***	0.34 (0.11, 13)	0.33 (0.10, 13)
3	0.18 (0.07, 12)	0.11 (0.08, 12)**	0.32 (0.02, 5)	0.26 (0.08, 5)
4	0.15 (0.09, 11)	0.06 (0.08, 11)**	0.30 (0.05, 5)	0.16 (0.09, 5)**
5	0.07 (0.04, 9)	0.02 (0.01, 9)***	0.16 (0.06, 4)	0.08 (0.05, 4)

Year 1 measurements were between 28/08/09 till 9/02/10,
Dates for years since wildfire, presented in Table 2
Standard deviation and number of events in parenthesis respectively
P-value <0.1*
P-value < 0.05 **
P-value < 0.01 ***

Table 6 Hydrograph analysis

		Median time from start of rainfall till start of runoff (min)		Median time of recession flow from peak discharge (min)	
Year since wildfire	n	Equatorial facing	Polar facing	Equatorial facing	Polar facing
1	11	30	29*	100	91
2	27	30	38**	106	289*
3	14	42	56**	183	356
4 and 5	7	54	62*	288	427

P-value < 0.05 *
P-value < 0.01 **

Table 7 Post-wildfire characteristics of forested catchments of contrasting aridity

Property	East Kiewa site				Stony Gully site			
AI	1.4				2.2			
Mean soil bulk density (g cm^{-3})	1.1 (0.33)[a], 0.83 (0.17)[b]				1.39 (0.14)			
Mean porosity calculated	0.58[c], 0.70[c]				0.48[c]			
Gravel (%)	12.2 (7.5)[d]				57.0 (13.1)[e]			
Year since wildfire	Year 1	Year 2	Year 3	Year 4	Year 1	Year 2	Year 4	Year 5
Average RC	0.03[f]	0.03[f]	0.02[f]	-	0.26 (0.14)	0.25 (0.10)	0.10 (0.10)	0.05 (0.04)
Mean ponded hydraulic conductivity (mm hr^{-1})	333 (287)[g]	-	619 (422)[h]	355 (282)[h]	1 (5) [1, 0]	16 (31) [13, 20]	-	22 (31) [25, 19]
Water repellency (%)	100[i]	71[i]	31[i]	11[i]	78 [100, 55]	79 [89, 68]	-	46 [42, 50]
Mean surface cover (vegetation and litter)	23 (21)[j]	59 (19)[j]	86 (23)[j]	93 (3)[j]	2 (5) [1, 4]	20 (17) [19, 21]	61 (23) [59, 62]	55 (25) [45, 64]

Standard deviation in parenthesis.

Square brackets study catchments, equatorial facing catchment, polar facing catchment.

[a]Sampled from areas adjacent to plots used for rainfall simulation, detailed in *Sheridan et al.* [2007] using the method described in this study.

[b]Sampled from areas adjacent to ring infiltration experiments detailed in *Sheridan et al.* [2007].

[c]Porosity calculated using solid particle density of 2.65 kg m^{-3} .

[d]Sample locations detailed in *Lane et al.* [2012], taken at 0-5 cm depth.

[e]Sampled at 0-7.5 cm depth.

[f] Due to the different hydrological processes to calculate RC for the East Kiewa sites storm flow identified in *Sheridan et al.* [2011] was separated from base flow using the method detailed in *Hewlett and Hibbert* [1967]. This was then used to calculate annual RC for these catchments using the sum of rainfall and sum of storm flow for each storm identified.

[g]Data from *Nyman et al.* [2010].

[h]Data summarised in *Sheridan et al.* [2007], year 3 measurements from March 2005 and September 2005, year 4 measurements from February 2006.

[i]Water repellency measured at mineral soil at East Kiewa Site *Sheridan et al.* [2007].

[j]Data from *Sheridan et al.* [2007].

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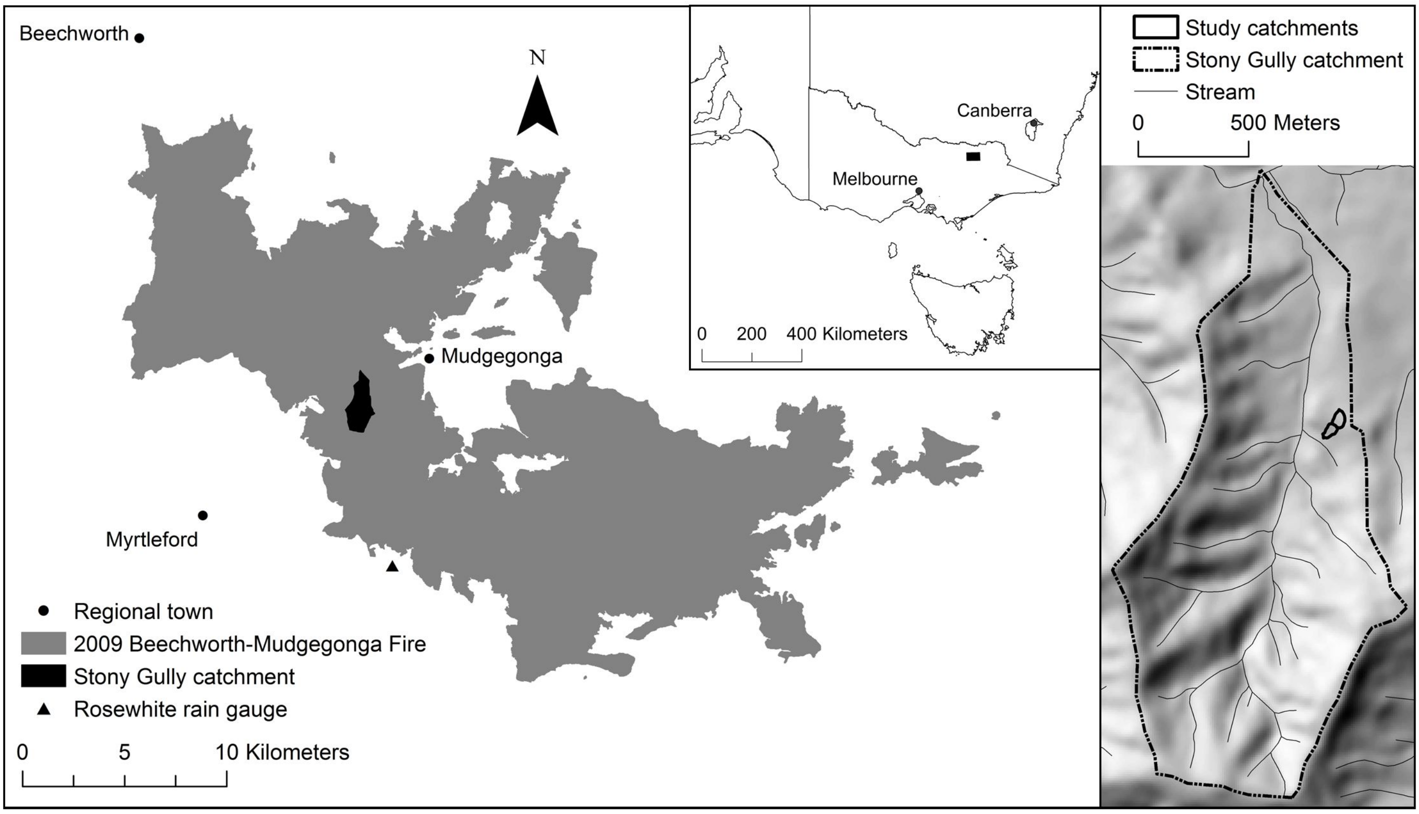
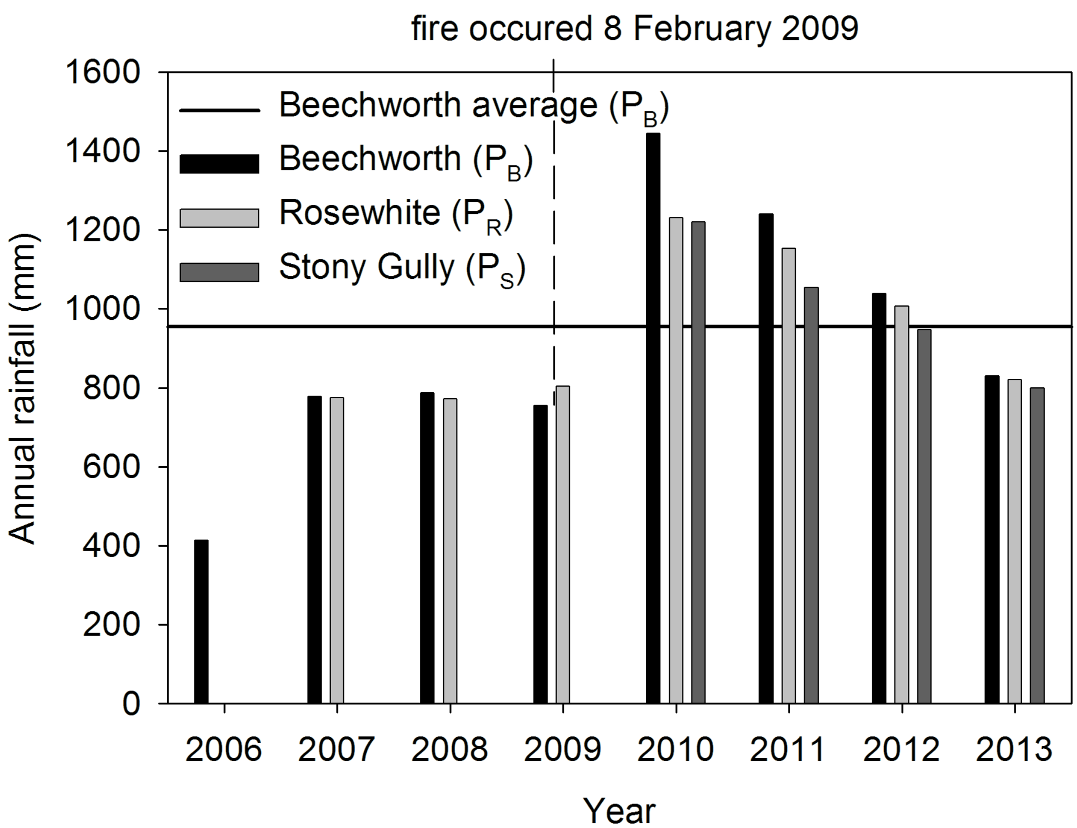
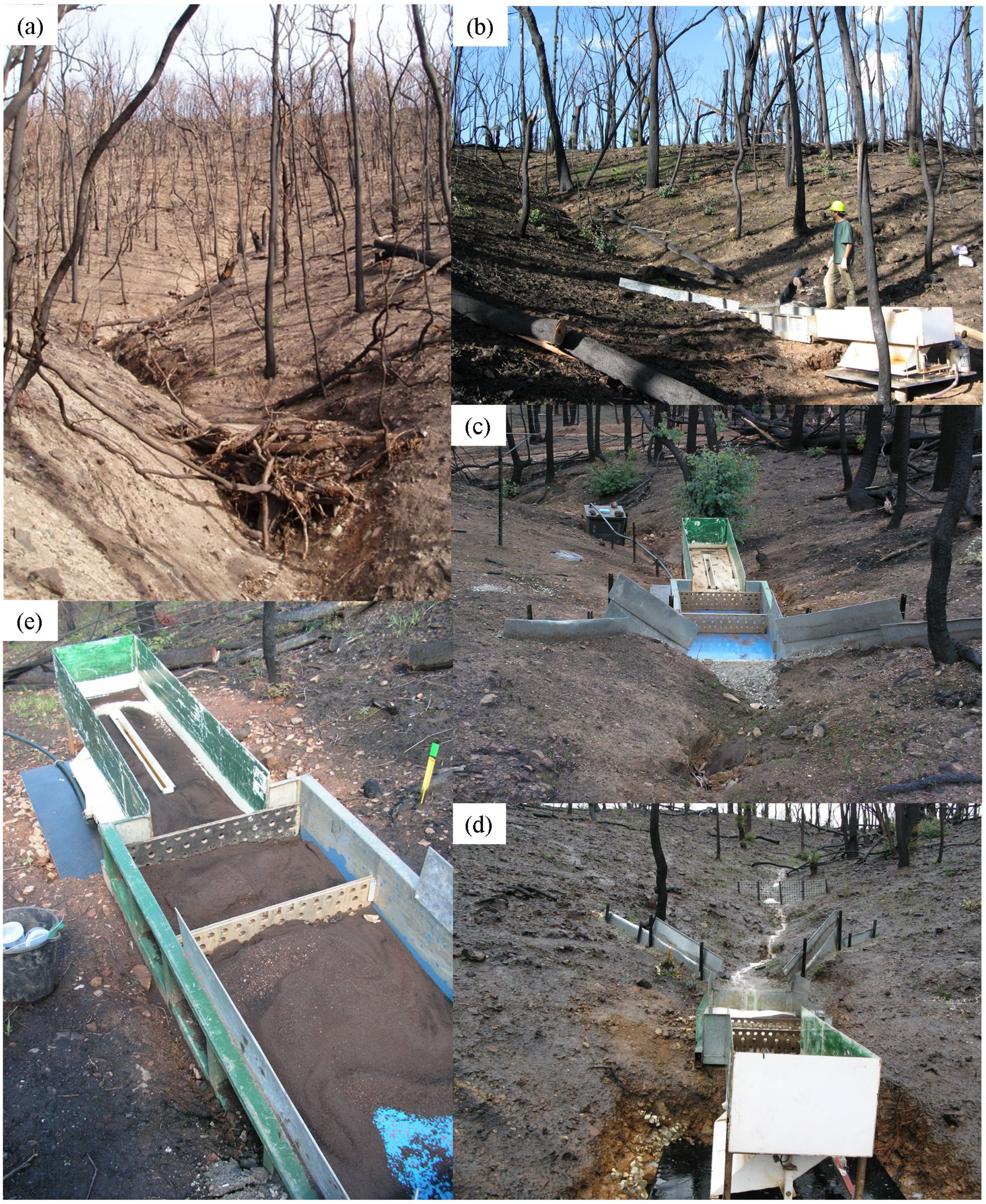
10. Figures

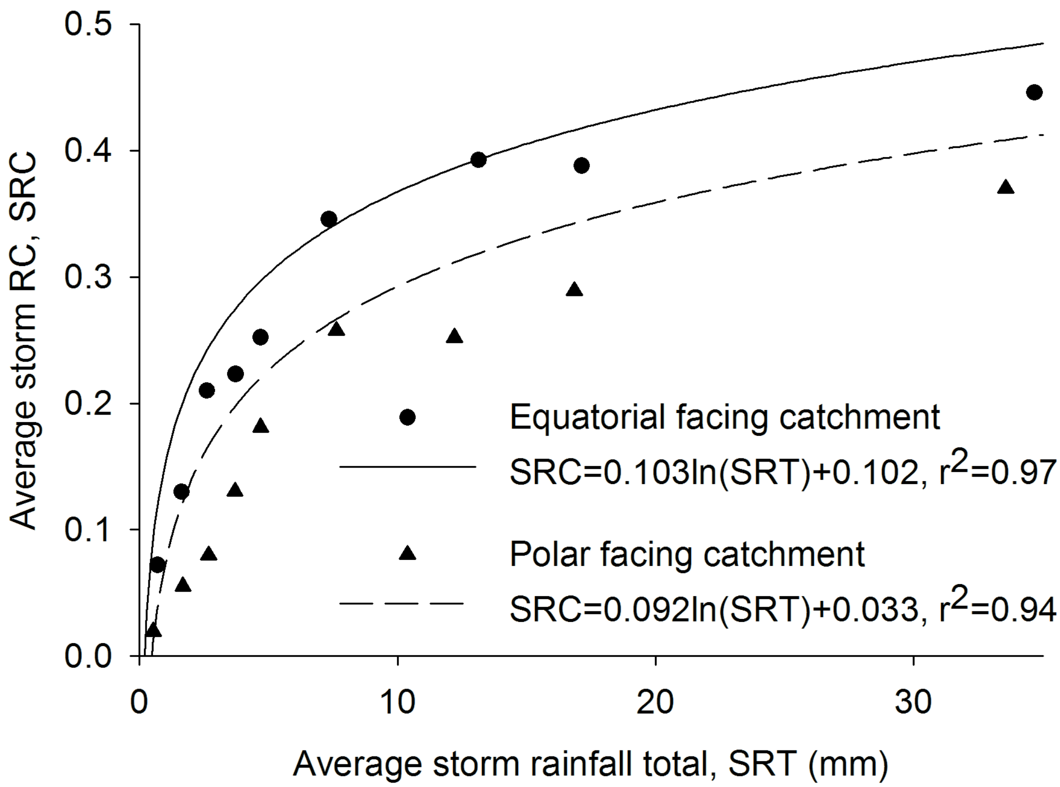
Figure 7 Time series of photographs from the base of each catchment.

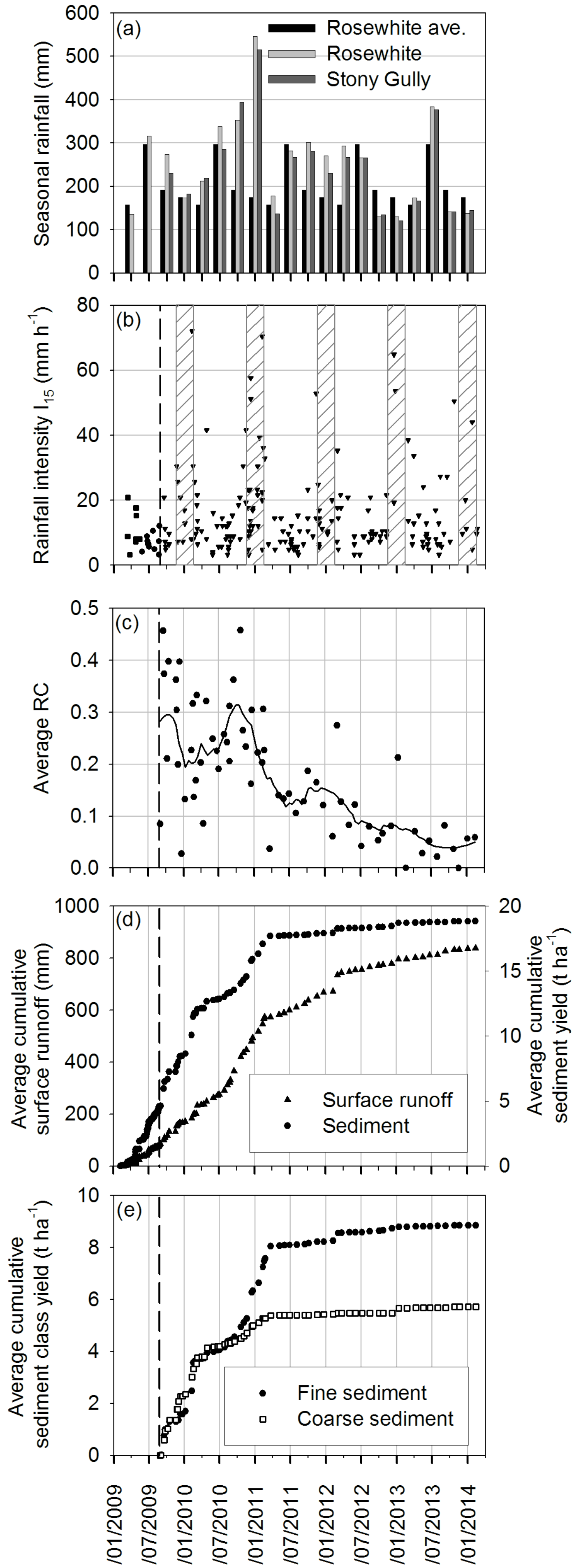
Figure 8 Site sevice interval, erodibility, sediment yield and peak 15 minute discharge, for each catchment


Beechworth
N
Mudgegonga
Myrtleford
Regional town
2009 Beechworth-Mudgegonga Fire
Stony Gully catchment
Rosewhite rain gauge
0 5 10 Kilometers
Canberra
Melbourne
0 200 400 Kilometers
Study catchments
Stony Gully catchment
Stream
0 500 Meters

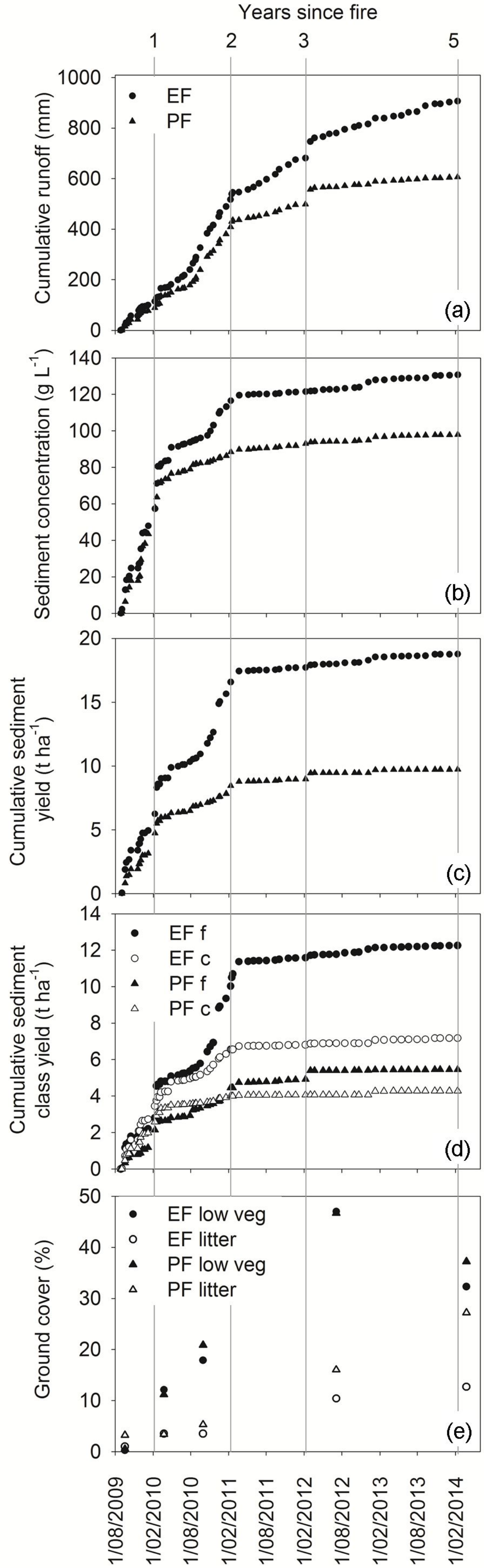

fire occured 8 February 2009
1600
1400
1200
1000
800
600
400
200
0
Annual rainfall (mm)
Beechworth average (P_B)
Beechworth (P_B)
Rosewhite (P_R)
Stony Gully (P_S)
2006
2007
2008
2009
2010
2011
2012
2013
Year


(a)
(b)
(c)
(d)
(e)

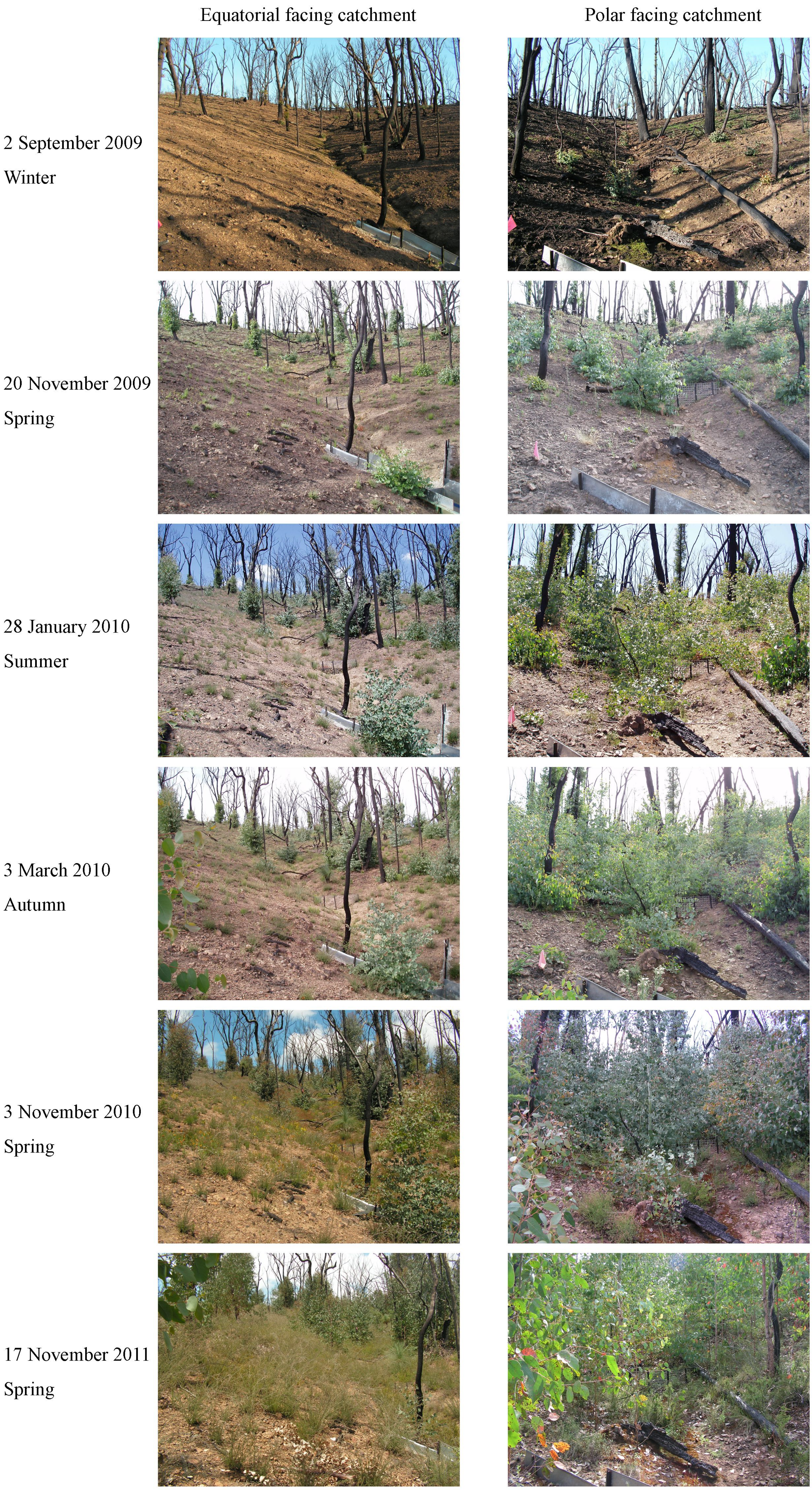

0.5
0.4
0.3
0.2
0.1
0.0
Average storm RC, SRC
0
10
20
30
Average storm rainfall total, SRT (mm)
Equatorial facing catchment
SRC=0.103ln(SRT)+0.102, r2=0.97
Polar facing catchment
SRC=0.092ln(SRT)+0.033, r2=0.94

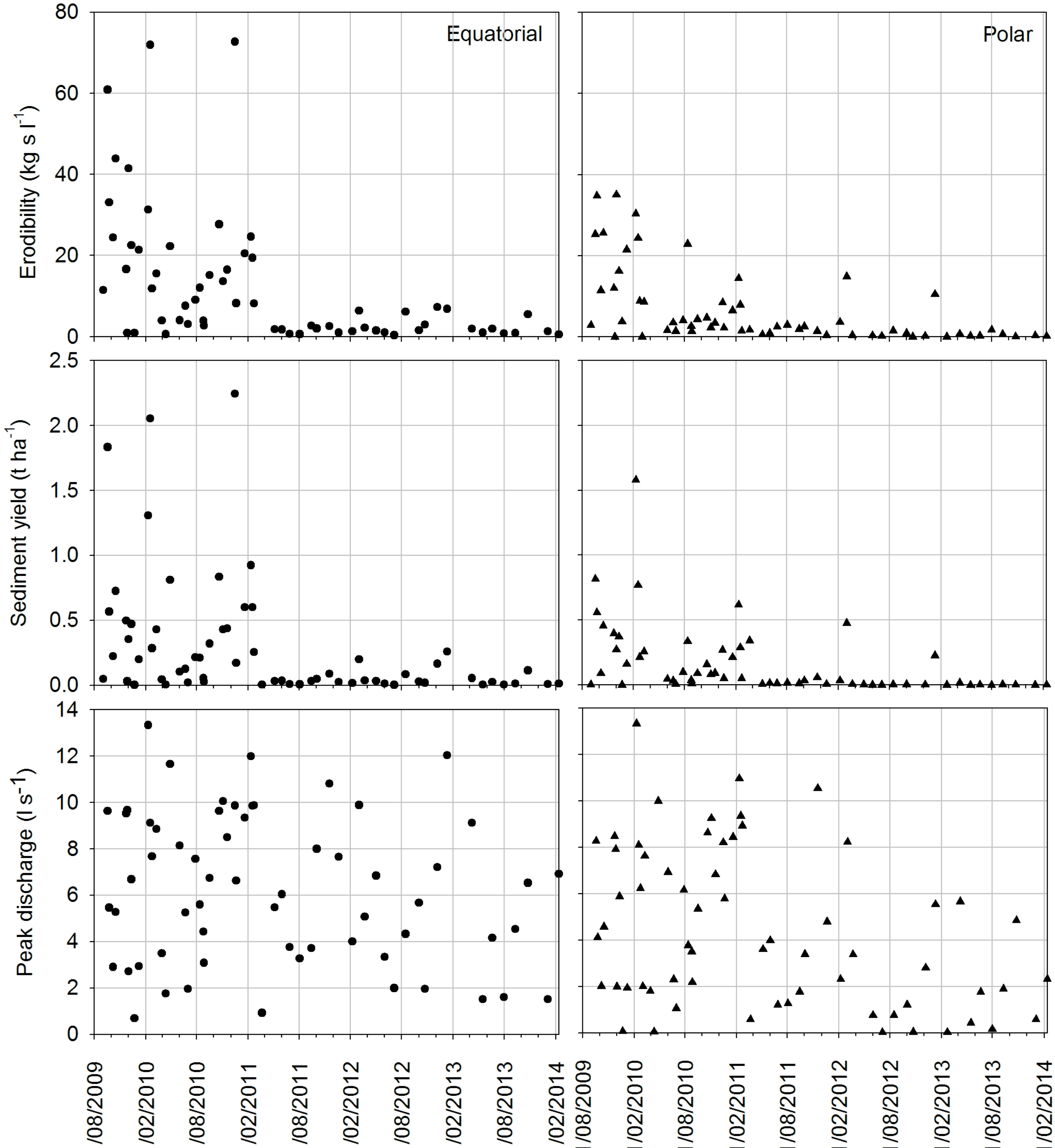


(a)
Rosewhite ave.
Rosewhite
Stony Gully
Seasonal rainfall (mm)
600
500
400
300
200
100
0
(b)
Rainfall intensity I_{15} (mm h^{-1})
80
60
40
20
0
(c)
Average RC
0.5
0.4
0.3
0.2
0.1
0.0
(d)
Average cumulative surface runoff (mm)
1000
800
600
400
200
0
Average cumulative sediment yield (t ha^{-1})
20
15
10
5
0
Surface runoff
Sediment
(e)
Average cumulative sediment class yield (t ha^{-1})
10
8
6
4
2
0
Fine sediment
Coarse sediment
1/01/2009
1/07/2009
1/01/2010
1/07/2010
1/01/2011
1/07/2011
1/01/2012
1/07/2012
1/01/2013
1/07/2013
1/01/2014



Years since fire
1
2
3
5
Cumulative runoff (mm)
EF
PF
(a)
Sediment concentration (g L-1)
(b)
Cumulative sediment yield (t ha-1)
(c)
Cumulative sediment class yield (t ha-1)
EF f
EF c
PF f
PF c
(d)
Ground cover (%)
EF low veg
EF litter
PF low veg
PF litter
(e)
1/08/2009
1/02/2010
1/08/2010
1/02/2011
1/08/2011
1/02/2012
1/08/2012
1/02/2013
1/08/2013
1/02/2014


Equatorial facing catchment
Polar facing catchment
2 September 2009
Winter
20 November 2009
Spring
28 January 2010
Summer
3 March 2010
Autumn
3 November 2010
Spring
17 November 2011
Spring


Equatorial
Polar
Erodibility (kg s l-1)
Sediment yield (t ha-1)
Peak discharge (l s-1)
80
60
40
20
0
2.5
2.0
1.5
1.0
0.5
0.0
14
12
10
8
6
4
2
0
1/08/2009
1/02/2010
1/08/2010
1/02/2011
1/08/2011
1/02/2012
1/08/2012
1/02/2013
1/08/2013
1/02/2014