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Runoff and erosion from Australia's tropical semi-arid rangelands: influence of ground cover for differing space and time scales

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Abstract:

This paper highlights the relevant issues influencing the amount and arrangement of ground cover in savanna rangelands in Australia, and presents field measurements from hillslope scale flumes, which demonstrate how runoff and sediment loss vary with spatial patterns in ground cover. Hillslopes with relatively high mean cover, but with small patches bare of vegetation, are shown to have between 6 and 9 times more runoff, and up to 60 times more sediment loss than similar hillslopes that do not contain bare patches. The majority of sediment lost from the hillslopes is composed of fine (suspended) rather than coarse (bedload) material, although the absolute sediment loads are comparatively low. These low loads are considered to be the result of lower than average rainfall during the measurement period (2002–2005) and the high and prolonged rates of historical hillslope erosion that have exhausted the erodible material from the A-horizon. The collected data also demonstrate that a large proportion of soil is lost during the initial 'flushing' period of runoff events.

The results presented have important implications for the management of savanna grazing systems by highlighting (i) the significance of bare patches in contributing to runoff and soil loss from hillslopes; (ii) the importance of having medium to high cover patches at the bottom of hillslopes for trapping and storing sediment and therefore reducing its entry into the stream network; and (iii) how maintenance of ground cover during the dry season reduces sediment concentrations in runoff occurring early in the wet season. Copyright © 2006 John Wiley & Sons, Ltd.

KEY WORDS hillslope runoff; sediment yield; savanna; spatial pattern; grazing

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INTRODUCTION

Tropical savannas or grasslands cover approximately one-fifth of Australia's land area (~1·5 million km^2) (Mott and Tothill, 1984) of which ~60% (or 0·9 million km^2) is used for beef cattle rearing. Tropical rangelands are characterized by open Eucalypt woodlands and grassland vegetation and receive ~70% of their annual rainfall in the 4 months between December and March (Bonnell and Williams, 1986; Townsend and Douglas, 2000). The extreme wet–dry climate regime experienced by these systems results in an erratic spatial distribution of water, sediments and nutrients, particularly at the <5 m^2 scale (Ludwig *et al.*, 1999) leading to a naturally 'patchy' arrangement of vegetation in the landscape. Cover is often irregularly distributed in distinct bands across hillslopes when cover is good, and can form irregular patterns in highly disturbed

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areas (Northup *et al.*, 2005). Further pressures including grazing, increase the vegetation patchiness of these systems, making them highly vulnerable to land degradation. The loss of sediments and nutrients from degraded landscapes not only has the potential to negatively impact downstream water quality and associated ecosystems, but can affect grazing production.

Due to the potential threat of sediment pollution on downstream areas, there has been a large research effort in recent years to determine the processes controlling water, sediment and nutrient loss from grazed savanna landscapes (e.g. Prosser *et al.*, 2002; Roth *et al.*, 2003). While it is established that ground cover plays a significant role in controlling the rates of runoff (e.g. Pressland *et al.*, 1991; McIvor *et al.*, 1995a,b; Connolly *et al.*, 1997) and sediment loss (e.g. McIvor *et al.*, 1995a, b; Scanlan *et al.*, 1996) in savanna landscapes, there has been little research on how the geographical pattern of high and low cover patches within the hillslope can influence runoff and sediment yield. Field observation by the authors suggests that the location of low cover patches, in close proximity to drainage lines, have an important influence on the amount of water and sediment lost to the stream network.

A patch can be defined as a distinct homogeneous soil surface and/or vegetation unit. The generation of patches within a landscape is a self-reinforcing process, and as long as patches remain intact they will continue to grow and concentrate resources (water, sediment and nutrients) through enhanced capture of runoff (Ludwig *et al.*, 2000). For example, vegetation patches within a hillslope have been shown to obstruct runoff and store runon (e.g. Reid *et al.*, 1999), enhance plant growth through storage of runon (e.g. Hodgkinson and Freudenberger, 1997), enhance soil infiltrability (e.g. Dawes-Gromadzki and Spain, 2003; Roth, 2004), and reduce hillslope losses of soil and water (e.g. McIvor *et al.*, 1995b; Wilcox *et al.*, 2003). Bare patches are also self-promoting because they can be a major source of water and sediment from the system, and if these resources are not trapped by another more conserving patch type, then these resources may be permanently lost from a hillslope.

In this paper we address: (i) the factors influencing the amount and spatial arrangement of ground cover in savanna rangelands in Australia; (ii) how sites with similar mean vegetation cover can have different water and sediment yields depending on the arrangement of cover on the hillslope; (iii) how low cover patches in close proximity to drainage lines influence hillslope runoff and sediment yield; (iv) the temporal relationship between rainfall, runoff and sediment loss on grazed hillslopes and (v) the infiltration properties of patches with different cover and soil conditions. We will address these issues using measured data from an experimental site in the Burdekin Catchment, North Queensland, Australia. In doing so, this paper will focus on hillslope erosion only. It is acknowledged that sediment and nutrients can be sourced from gully and bank erosion; however, these sources are beyond the scope of this paper.

FACTORS INFLUENCING THE ARRANGEMENT OF GROUND COVER

Rangeland systems in good condition are characterized by a large number of highly connected patches that efficiently capture, retain and utilize scarce resources within the landscape. They can therefore be considered conservative systems (Tongway and Ludwig, 1997). When the number, diversity and connection between patches are reduced, a system is said to be less conserving or 'leaky' (Ludwig *et al.*, 2006). There are a number of processes that occur in rangeland systems in Australia that increase the leakiness of these systems. Such processes include grazing, introduced pastures, fire and tree clearing.

Grazing can cause a loss of ground cover (Milchunas *et al.*, 1988; Freudenberger *et al.*, 1997), result in patchiness related to selective grazing of more palatable areas (Sallaway and Waters, 1994), increase soil compaction in rangeland systems (Willatt and Pullar, 1983; Okin, 2002) and alter the biological and hydraulic properties of the soil (Holt *et al.*, 1996; Roth, 2004).

Introduced pastures (e.g. those dominated by *Bothriocloa pertusa*) which were brought in to increase biomass in savanna areas for the grazing industry have, in some cases, been shown to have lower runoff and soil movement than native pastures (e.g. those dominated by *Heteropogon contortus*) when cover is low

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(<30%) (Pressland *et al.*, 1991; Scanlan *et al.*, 1996). However, total soil loss from both introduced and native pastures is reduced once ground cover exceeds 30% and McIvor *et al.* (1995b) suggest that the differences in runoff between woodlands, cleared areas and pasture are primarily due to differences in soil cover rather than species composition *per se*.

Fire can also alter the patch structure of savanna ecosystems and the timing of the fire appears to be the important element influencing water and sediment yields (Townsend and Douglas, 2000). Field studies in a grazed savanna landscape by Bonnell and Williams (1987) found that there was no statistical difference in sediment concentration following low intensity grass fires, although they did observe small changes in both overland flow and sediment transport at a number of sites which were attributed to the alteration of surface cover.

The effect of tree clearing on rangeland ecosystem structure and the resultant changes in water and sediment yield has not been well studied in Australia. Ludwig and Tongway (2002) found that when savannas are cleared of trees and woody debris, and developed into improved pasture systems, both exotic and native perennial grass increased in cover. Other studies have shown that killing trees and establishing improved pasture had little or no effect on water balance, runoff or soil loss characteristics (Prebble and Stirk, 1988; McIvor *et al.*, 1995b). For sediment load of rivers, however, the location of trees may be more important than the area covered by trees, as riparian strips intercept substantial sediment movement from upslope (van Noordwijk *et al.*, 1998). In general, if tree clearing and any associated land use change expose and/or disturb the soil surface then water and sediment loss is likely to increase.

There is a good conceptual understanding of how the spatial arrangement of patches influences water and sediment yield in rangeland and arid systems in Australia (e.g. Ludwig *et al.*, 2005; Dunkerley and Brown, 1995); however, there is very little data available to quantify the link between the spatial arrangement of cover and hydrological response. There is even less research on how disturbance will influence patch arrangement and subsequently water and soil loss.

There have been a range of studies looking at measuring and modelling hillslope water and sediment yield processes in Australian rangelands, although most of this research treated vegetation as an 'average' cover and has not specifically looked at the arrangement of cover within the study site of interest (e.g. Bonnell and Williams, 1986, 1987; McIvor *et al.*, 1995b; Scanlan *et al.*, 1996; Connolly *et al.*, 1997). In general, these studies suggest that a threshold exists such that when the percent of vegetation cover is less than 30–40%, runoff and soil loss dramatically increase.

Outside of northern Australia, Reid *et al.* (1999), Wilcox *et al.* (2003) and Bromley *et al.* (1997) looked at the hydrologic or hydraulic function of runoff and erosion dynamics of different patch types on pinon–juniper, semi-arid woodland and tiger bush hillslopes, respectively. These studies found that bare and vegetated patches played very different roles in terms of water and sediment generation, movement and storage on a hillslope. Sallaway and Waters (1994) found that the spatial arrangement of pasture patches had a marked effect on the hydrology of a catchment with the peak runoff rate being dependent on patch size and arrangement. Similarly, Boer and Puigdefabregas (2005) used a simulation approach to look at how hillslope water and sediment yield are affected by the variation in the spatial correlation structure of vegetation and soil patterns. Their results suggest that the spatial organization of bare and vegetated surfaces alone can have a substantial impact on predicted storm discharge and erosion.

The recent research described above provides further evidence that the arrangement of patches within a hillslope rather than the average ground cover, has important implications for the amount of water and sediment lost from hillslopes, particularly in semi-arid environments. Unlike the above-mentioned research, the work in this paper is not so focused on understanding the hydrologic or hydraulic function of the runoff and erosion dynamics of different patch types; nor does it assess runoff at hourly or minute time interval. Here, we are interested in the net effect of individual events integrated over an entire wet season (1–5 months). This follows because there is no such thing as an 'average' event in the dry tropics and the runoff generated from individual events are dependent on the antecedent conditions imposed by the timing and intensity of previous rainfall events. In addition, the relationship between runoff generation and sediment transport at the hillslope

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scale is known to have elements of non-linearity and is often threshold based (Boer and Puigdefabregas, 2005). Therefore, this paper is focused on understanding the effect of the spatial arrangement of cover on water and sediment yield at the bottom of a hillslope on a seasonal time scale. We will do this using measured data from a number of hillslopes in a rangeland area of North Queensland, Australia.

These results have important implications for understanding the effect of disturbance, in particular, the influence of grazing (stocking density, carrying capacity, fencing and stock rotation) on the water quality delivered to downstream water bodies. Although it is acknowledged that observations made at the plot scale cannot be linearly translated to the catchment scale (Ludwig and Tongway, 2002), it is hoped that the research presented in the paper can eventually be coupled with larger scale remote sensing approaches such as the landscape leakiness concepts presented in Ludwig *et al.* (2006) and hillslope sediment delivery ratio concepts in Lu *et al.* (2003).

STUDY AREA

This study was carried out in Weany Creek, a 13 km^2 sub-catchment of the Burdekin catchment in North Queensland, Australia. The Burdekin catchment is $\sim$130 000 km^2 and is the second largest catchment draining into the Great Barrier Reef World Heritage Area (GBRWHA). It is characterized by Eucalypt savanna woodlands, and apart from the rainforest-dominated humid fringe in the north-east, receives between 400 and 650 mm of rain each year. Ninety percent of the catchment is utilized for beef production.

A number of studies have shown that sediment discharge from the Burdekin catchment since European settlement is between 3 and 15 times greater than prior to settlement (Furnas, 2003; Neil *et al.*, 2002; McCulloch *et al.*, 2003). Moreover, there is increasing evidence that excessive sediments and nutrients from these areas are having adverse effects on the reef system (Fabricius, 2005).

The Weany Creek catchment (S19°53′06·79″, E146°32′06·65″) is located on a cattle property, Virginia Park Station, that has been grazed for more than 100 years (personal communication, Rob Bennetto, station owner). The area is representative of the highly erodible ‘gold-fields’ country between Townsville and Charters Towers in North Queensland. The gently sloping valley sides are composed primarily of red, texture contrast soils that overlie a granodiorite (Red Chromosols, Rogers *et al.*, 1999; corresponding to Rhodustalfs, Soil Survey Staff, USDA, 1994). Yellow to brown texture contrast soils with dispersive, natric B-horizons (Yellow and Brown Sodosols, Rogers *et al.*, 1999; corresponding to Natrustalfs, Soil Survey Staff, USDA, 1994) can also be found in large areas of the lower foot-slopes and large bare scald patches are present on the colluvial slopes adjacent to many gully and stream networks. The soils in the Weany Creek area are generally low in fertility, due to their surface textural properties and heavy grazing pressure; their surfaces are particularly prone to crusting and hard setting. The canopy vegetation is composed primarily of narrow-leafed ironbark (*Eucalyptus creba*) and red bloodwood (*Eucalyptus papuana*) and the ground cover is dominated by the exotic, but naturalized stoloniferous grass Indian couch (*B. pertusa*).

METHODS: MEASURING RUNOFF, EROSION AND INFILTRATION

To measure water and sediment yields from hillslopes with different patch arrangement, three hillslopes with similar morphological structure, but different cover arrangements were chosen (Table I). The three hillslopes were located within 400 m of each other in the same field. On each hillslope, flumes were installed to quantify runoff and sediment loss following rainfall events (Figure 1). Data were collected over three wet seasons from November 2002 to February 2005. For the remainder of this paper the sites will be referred to as Flume 1, Flume 2 and Flume 3.

Flume 1 is much larger than Flumes 2 and 3, and was chosen specifically to look at water and sediment yield on the large, or whole of hillslope, scale. Flume 1 is representative of the classic ‘patchy’ cover distribution of savanna landscapes (Figure 2(a)). Flumes 2 and 3 are of similar size, yet have very different cover patterns.

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Table I. Description of the major properties of the hillslope flume site

	Flume 1—Large flume	Flume 2—Grass flume	Flume 3—Scald flume
Area (m^2)	11 930	2031	2861
Mean slope (%)	3·9	3·1	3·6
Slope length (m)	240	130	150
Soil type[a]	Red chromosol (Dalrymple series, eroded phase)	Red chromosol (Dalrymple series, eroded phase)	Transition from red chromosol to yellow sodosols (Bluff series)
Mean depth of A-horizon (mm)[b]	~8 cm (varies from 5 to 40 cm)	~9 cm (varies from 1 to 20 cm)	~8 cm (varies from 0 to 15 cm)

[a] Rogers *et al.* (1999).
[b] Note: on both Flume 1 and 3 there are small areas of active sheet and rill erosion where the A-horizon has been totally removed.

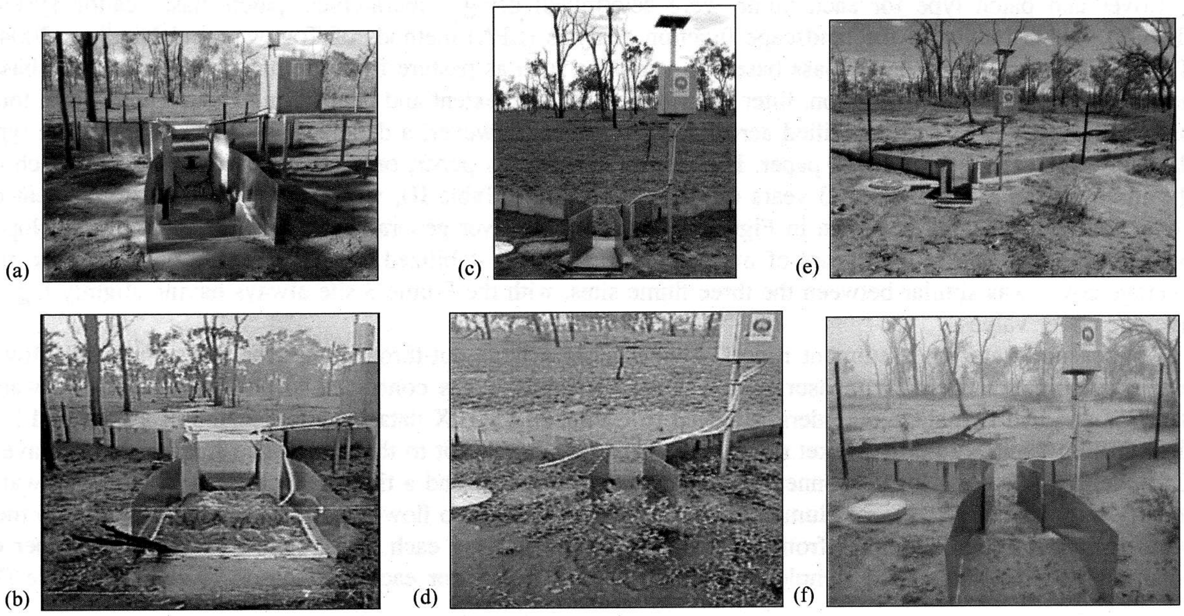

Figure 1. Images of the three flume sites: (a) Flume 1 during the dry season; (b) Flume 1 during a runoff event; (c) Flume 2 during the dry season; (d) Flume 2 during a runoff event; (e) Flume 3 during the dry season; and (f) Flume 3 during a runoff event

Flume 2 has relatively uniform cover over the whole slope (Figure 2(b)), whereas Flume 3 has areas of medium to high cover at the top of the slope, but low cover in the form of a large bare patch at the base of the slope adjacent to the flume (Figure 2(c)). The variation in cover on each of the flume hillslopes is a function of (i) the variable grazing pattern of cattle (ii) the natural distribution of soils and vegetation and (iii) the size and location of each flume on the hillslope. Both Flumes 1 and 3 are located at the base of the hillslope and are influenced by the presence of the exposed highly erodible sodic soils adjacent to the riparian zone. These soils are prone to gully formation, a process that has been initiated down slope of both Flumes 1 and 3. Cattle also tend to prefer grazing and traversing near the riparian zones (presumably due to the access to shade), which results in higher levels of disturbance in these lower hillslope areas. Therefore, Flumes 1 and 3 have a patchier distribution of cover due to the higher proportion of bare soil at the bottom of the hillslope compared to the upper sections. Flume 2 is located half-way down the hillslope (so as to avoid the bare patches downslope) and has relatively uniform cover, as either the exposed sodic soils or preferential

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cattle grazing do not influence it. Flume 1 being larger, also has a flow line down the centre of the hillslope (thalweg) that concentrates flow. This flow line is more of a depression than a defined channel; however, during the larger rainfall events it concentrates flow from the hillslope (Figure 1(b)). Flumes 2 and 3 do not have flow lines and therefore move water across the hillslope as sheet flow (see Figure 1).

The hillslopes containing the flumes had stocking rates that approximated one adult cow (Braham species) to every 10 ha. The stocking rate is calculated using a forage budget where the aim was to use 35% of the standing dry matter (pasture). The minimum residual grass yield at the end of each dry season was ~400 kg of matter per hectare. Cattle were also excluded from the flume hillslopes whenever possible during the wet season (known as wet season spelling) (Table II), as this is considered to promote pasture growth for the following dry season.

To determine the area, slope and topography of each flume, the sites were surveyed at approximately 4 m × 2 m spacing using a Wild TC 1000 total station. The data were then converted to a DEM profile using TOPOGRID within ArcInfo. The catchment boundary of each hillslope was determined using the catchment delineation function within ArcInfo.

Cover and patch type for each flume were determined using a hierarchical patch classification system (HPCS), which builds on the landscape function analysis (LFA) methods of Tongway and Hindley (2004). The HPCS determines a patch class based on variables such as pasture form, dominant pasture group, basal area, total cover, folia contribution, litter contribution, erosion extent and deposition extent. There was a total of 28 different patch types identified across the study area; however, a detailed discussion of the patch type data is beyond the scope of this paper. For the purpose of this paper, only 'average cover' (%) for each of the three hillslope sites for the 3 years of study is reported (Table II), although the spatial arrangement of cover for each hillslope is shown in Figure 2. The average cover generally declined on all of the hillslopes between the first and second years of measurement, and then stabilized in year three. In any one year, the average cover was similar between the three flume sites, with the Flume 3 site always having slightly higher average cover values.

To measure water and sediment runoff, Flume 1 has a large cut-throat flume for measuring high flows, and a combination weir for measuring low flows. The flume was connected to an ISCO automatic water sampler and had two stage recorders, attached to Campbell CR10X data loggers, located in a high and low flow stilling well. A tipping bucket rain gauge was located adjacent to the flume. The smaller flumes have a Campbell CR10X data logger connected to a single stilling well and a tipping bucket rain gauge. The water quality samples collected from Flume 1 were stratified according to flow depth, and for Flumes 2 and 3 they were collected as bulk samples from a collecting drum following each major runoff event. The number of total suspended solids (TSS) samples collected for each flume, for each wet season is given in Table IV.

Table II. Mean cover (%), rainfall (mm) and grazing conditions for each flume site for the 3 years of data collection

		2003	2004	2005
Flume 1	Cover (%) (SD)	61 (17·6)	34 (6·6)	44 (22·6)
	Rainfall (mm)	250	238	299
Flume 2	Cover (%) (SD)	58 (10·3)	38 (4·95)	34 (14·8)
	Rainfall (mm)	~250[a]	255	298
Flume 3	Cover (%) (SD)	68 (19·8)	46 (14·3)	47 (20·7)
	Rainfall (mm)	~250[a]	221	255
Wet season spelling[b] conditions		January 2003–December 2003 no spelling, 25% utilization (due to little pasture growth)	December 2003–January 2005 full wet season spelling (4 months), 35% utilization	February 2005–August 2005 full wet season spelling (6 months), 35% utilization

[a] Separate rain gauges were not installed at flumes 2 and 3 until the second year of measurement.
[b] Spelling refers to a period without cattle.

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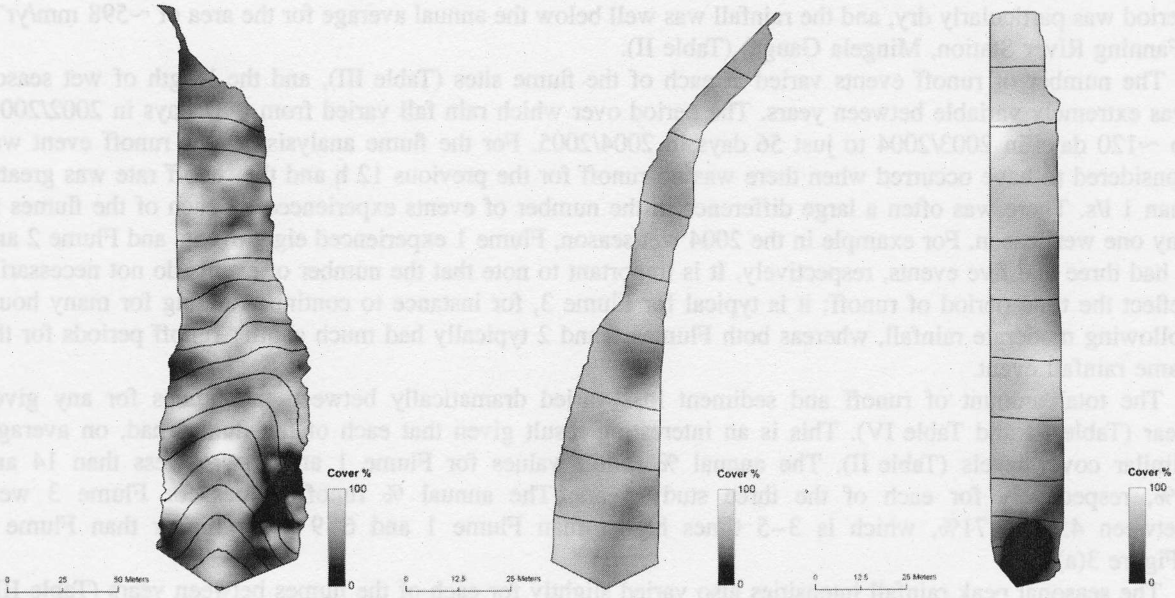

Figure 2. Representation of the measured cover (%) on each of the three hillslope flume sites at the beginning of the measurement period (October 2002). Flume 1 on the left (a), Flume 2 in centre (b) and Flume 3 on the right (c). Note scale differences between Flume 1 and Flumes 2 and 3. The contour interval is 0·5 m

All samples were returned to the lab for the analysis of EC, pH, turbidity, TSS, sediment size, total and dissolved nitrogen and phosphorus. TSS samples are considered to represent the silt (0·002–0·06 mm) and clay (<0·002 mm) sediment fractions. Bedload samples (that are generally between 0·063 and 64 mm) were collected manually from bedload traps in each of the three sites and were assessed for volume and grain size distribution. To estimate sediment loads the arithmetic mean approach (after Letcher *et al.*, 1999) was applied to data collected from each event when both concentration and discharge data were available, otherwise wet season average concentration values were applied.

The infiltration properties of discrete patches with different cover (%) were measured in areas adjacent to the flume sites. Thirteen sites that match the patch/cover classes on each of the hillslopes flume sites were selected. For each patch, infiltration was measured in replicate (three runs on each), along with bulk density (g/cm^3) (data not shown). The saturated hydraulic conductivity (K_{sat}) was determined using a hood infiltrometer (UGT, 2005) as an approximation of the saturated or equilibrium soil infiltration rate (mm/h). This method, which is analogous to the disc permeameter method, has the advantage that it allows for the determination of flow through undisturbed soil surfaces by placing a plastic hood over the soil and sealing it under tension with sand filled rim, allowing for unimpeded flow. The infiltration rates measured using this method are considered to be reasonably close to the equilibrium infiltration rates for these soils due to the short time frames required to bring the initial infiltration rate to within 10% of the final infiltration rate (see Roth, 2004, who found good agreement between infiltration rates determined with a rainfall simulator and those determined using the hood permeameter).

RESULTS

Flume monitoring results

During the 28 month study period, the flume sites received ~705 mm of rainfall which produced between 1 and 8 runoff events during each of the three wet seasons. It is important to note that the 3-year study

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period was particularly dry, and the rainfall was well below the annual average for the area of ~598 mm/yr^{-1} (Fanning River Station, Mingela Gauge) (Table II).

The number of runoff events varied at each of the flume sites (Table III), and the length of wet season was extremely variable between years. The period over which rain fall varied from ~37 days in 2002/2003, to ~120 days in 2003/2004 to just 56 days in 2004/2005. For the flume analysis, a new runoff event was considered to have occurred when there was no runoff for the previous 12 h and the runoff rate was greater than 1 l/s. There was often a large difference in the number of events experienced by each of the flumes in any one wet season. For example in the 2004 wet season, Flume 1 experienced eight events and Flume 2 and 3 had three and five events, respectively. It is important to note that the number of events do not necessarily reflect the time period of runoff; it is typical for Flume 3, for instance to continue running for many hours following moderate rainfall, whereas both Flumes 1 and 2 typically had much shorter runoff periods for the same rainfall event.

The total amount of runoff and sediment loss varied dramatically between the flumes for any given year (Table III and Table IV). This is an interesting result given that each of the flumes had, on average, similar cover levels (Table II). The annual % runoff values for Flume 1 and 2 were less than 14 and 8%, respectively for each of the three study years. The annual % runoff values for Flume 3 were between 45 and 71%, which is 3–5 times higher than Flume 1 and 6–9 times higher than Flume 2 (Figure 3(a)).

The seasonal peak rainfall intensities also varied slightly for each of the flumes between years (Table III). The rainfall intensities are based on rainfall data collected at 1 min intervals, and vary between 108 and 144 mm/h in 2004, and between 60 and 132 (mm/h) in 2005 for the three flumes. The exception is the 2003 wet season that had a peak rainfall intensity of 108 mm/h for all of the flumes as the rainfall data for that year were based on a single rainfall logger located adjacent to the Flume 1. The variability in peak rainfall intensities highlights the subtle, but important variation in the rainfall distribution experienced by the three flumes although they are no more than 400 m s apart.

Table III. Summary of rainfall and runoff characteristics for the three flumes. The rainfall intensity data is based on rainfall collected at 1 min intervals

Year		Flume 1	Flume 2	Flume 3
2003	Total rainfall contributing to runoff (mm)	168	89	158
	Total measured runoff (mm)	16	5	102
	Peak rainfall intensity (mm/h)	108	108	108
	% runoff	9·5	5·6	71·0
	Peak runoff rate (mm/h)	33	11	19
	No. of runoff events	2	1	4
2004	Total rainfall contributing to runoff (mm)	238	255	>156[a]
	Total measured runoff (mm)	32	11	65
	Peak rainfall intensity (mm/h)	126	108	144
	% runoff	13·4	4·0	53·0[b]
	Peak runoff rate (mm/h)	60	22	51
	No. of runoff events	8	3	5
2005	Total rainfall contributing to runoff (mm)	299	299	255
	Total measured runoff (mm)	32·47	21·34	117·31
	Peak rainfall intensity (mm/h)	60	120	132
	% runoff	10·7	7·0	45·9
	Peak runoff rate (mm/h)	13	12	23
	No. of runoff events	2	2	2

[a] Note this is an underestimate as the logger failed during an event.
[b] This is an approximation based on altered rainfall and runoff values due to logger failure.

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Table IV. Summary of sediment loss results from the three flumes

Year		Flume 1	Flume 2	Flume 3
2003	Fine soil loss (t/ha) (n = no. of TSS samples analysed)	0·27 ($n = 3$)	ND	2·92 ($n = 5$)
	Coarse sediment loss (t/ha)	0·0025	0·0032	0·18
	Total sediment loss (t/ha)	**0·2725**	**>0·0032**	**3·1**
	Bedload as % of total loss	0·91	ND	5·8
2004	Fine soil loss (t/ha) (n = no. of TSS samples analysed)	0·25 ($n = 19$)	0·04 ($n = 3$)	1·65 ($n = 2$)
	Coarse sediment loss (t/ha)	0·00077	0·00025	0·807
	Total sediment loss (t/ha)	**0·25077**	**0·04025**	**2·46**
	Bedload as % of total loss	0·31	0·63	49·1
2005	Fine soil loss (t/ha) (n = no. of TSS samples analysed)	0·09 ($n = 28$)	0·06 ($n = 3$)	1·83 ($n = 3$)
	Coarse sediment loss (t/ha)	$0·06 * 10^{-3}$	NA	0·68
	Total sediment loss (t/ha)	**0·09406**	**>0·06**	**2·51**
	Bedload as % of total loss	0·06	—	27·1

ND, no sample analysed due to sampler malfunction; NA, no sample produced.

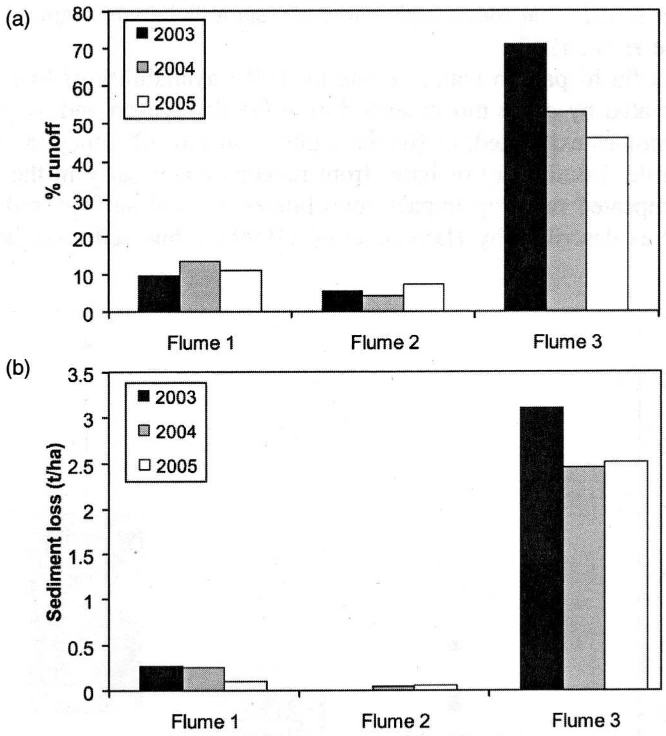

Figure 3. Variation in (a) % runoff and (b) total soil loss (t/ha) from the three flumes at Virginia Park over the 3-year study period

The seasonal peak runoff rates also varied considerably between each of the flumes, with Flume 1 consistently having the highest runoff rate (between 13 and 60 mm/h), followed by Flume 3 (between 19 and 51 mm/h) and then Flume 2 (between 11 and 22 mm/h) (Table III). The slightly higher peak runoff rates experienced by Flume 1 can be attributed to the larger contributing catchment area, as well as the channelized flow conditions that occur on that hillslope. It is interesting to note that there is no consistent relationship between the peak rainfall intensities and peak runoff rates experienced for any of the flumes (and this will be discussed in more detail below).

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The sediment yield data followed a similar pattern with Flume 1 losing between 0·090 and 0·270 t ha^{-1} yr^{-1}, Flume 2 between 0·003 and 0·060 t ha^{-1} yr^{-1} and Flume 3 between 2·51 and 3·100 t ha^{-1} yr^{-1}, over the 3-year study period (Figure 3(b)). Both the TSS concentrations (Figure 4) and amount of bedload (Table IV) were consistently higher in Flume 3 than in either Flumes 1 or 2. With the exception of one year (2004) for Flume 3, load of suspended sediments dominates sediment yield.

The temporal relationship between measured rainfall, runoff and sediment loss

In addition to computed annual runoff and sediment loss from each of the three flumes, data were collected during a number of individual events in Flume 1. For most of the events, but most evident in the early wet season events, TSS concentrations are characterized by clockwise hysteresis, where higher TSS concentrations were obtained on the rising limb of the hydrograph than the falling limb despite the relatively low discharge values (Figure 5). In any one year, the hysteresis was more pronounced for individual events if there was a considerable time delay between the flow events (e.g. 1 month). When individual events were spaced closer in time (e.g. days apart) the hysteresis was much stronger for the initial rather than subsequent events. For most of the events, there was a poor correlation between runoff (l/s) and TSS (g/l). As a result, knowledge of runoff alone will be a poor predictor of sediment loss, particularly for early wet season events. This result is quite different to other studies that found high linear correlations between runoff and sediment yield at the hillslope scale (e.g. Lane *et al.*, 1997).

The hysteresis or 'first flush' pattern could be due to (i) the availability of loose sediment on the ground surface that has been created by cattle movements during the dry season and as the wet season progresses, this surface sediment becomes exhausted; or (ii) the higher raindrop efficiency in the early wet season when soils are loose (from cattle disturbance) or bare (from reduced cover early in the wet season)—as the wet season progresses, the repeated raindrop impact consolidates the soil surface, reducing the opportunity for soil detachment; or (iii) as described by Hairsine *et al.* (1999), a fine sediment layer may have formed on

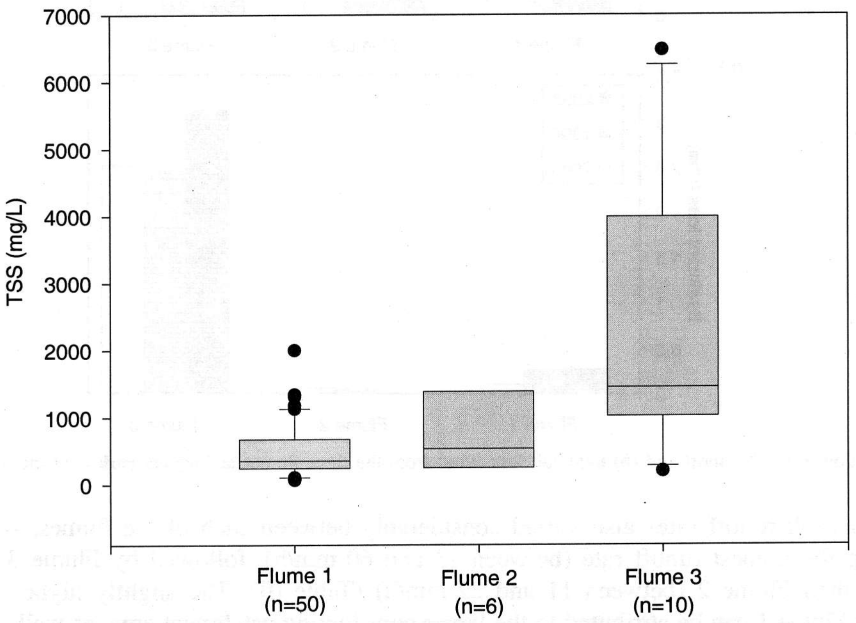

Figure 4. Range of TSS concentrations measured from the different flume sites over the 3-year study period. Note more samples were collected from Flume 1 due to the ability to collect samples at low flows using the ISCO autosampler. Concentrations for Flume 1 are based on individual flow events. For Flumes 2 and 3 the samples were collected in a bulk sampler and therefore some of samples are based on individual events and others are bulk samples taken over a series of events in close succession (usually within 24 h)

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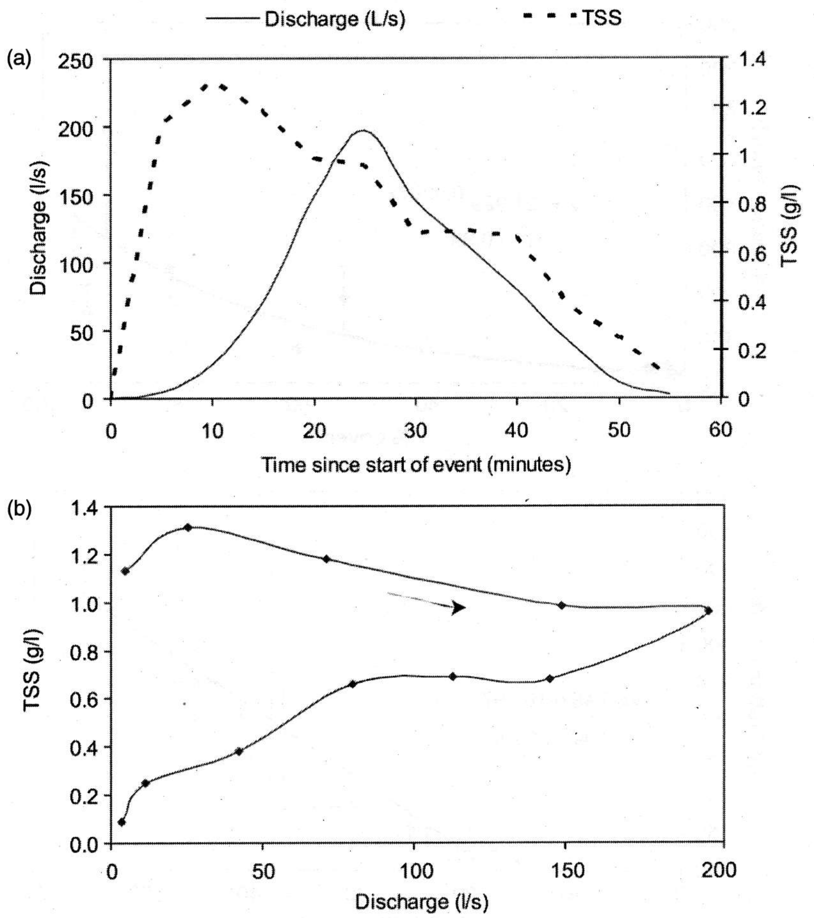

Figure 5. (a) Relationship between discharge and total suspended sediment (TSS) for a typical runoff event for Flume 1 (this event occurred on 13/12/2004) and (b) the strong clockwise hysteresis for the same event demonstrating the strong first flush process

the surface which acts to shield the underlying soil from erosive stresses of runoff and raindrop impact—the erosive potential required to remove this surface layer is much lower than for the underlying soil matrix, hence the 'first flush' or (iv) the fact that the amount of cover on the hillslope is lower at the beginning of the dry season, and as the wet season progresses, the grass grows and the opportunity for infiltration and trapping of water and sediment is increased. In conjunction with the increased grass growth, there may also be an element of sediment mobilization, storage and remobilization occurring where by sediment is deposited upslope of the flume at the end of one event and then is remobilized at the beginning of the next event.

Infiltration properties of different patch types

The results from the hood permeameter infiltration experiments produced a significant exponential fit between percent ground cover and infiltration rate (Figure 6(a)). However, variability of the relationship increases significantly at higher cover levels, reflecting the increasing role of factors other than cover. Previous work has shown that soil surface condition (SSC), of which cover is only one factor, is a better predictor of infiltration (Tongway and Hindley, 2004; Roth, 2004). This is shown in Figure 6(b), where measured infiltration rates for each patch type are plotted against scored SSC infiltration values (after Tongway and Hindley, 2004). As soil biological activity increases within the patches, SSC improves. This provides a means of crust disruption, leading to higher infiltration rates (Roth, 2004).

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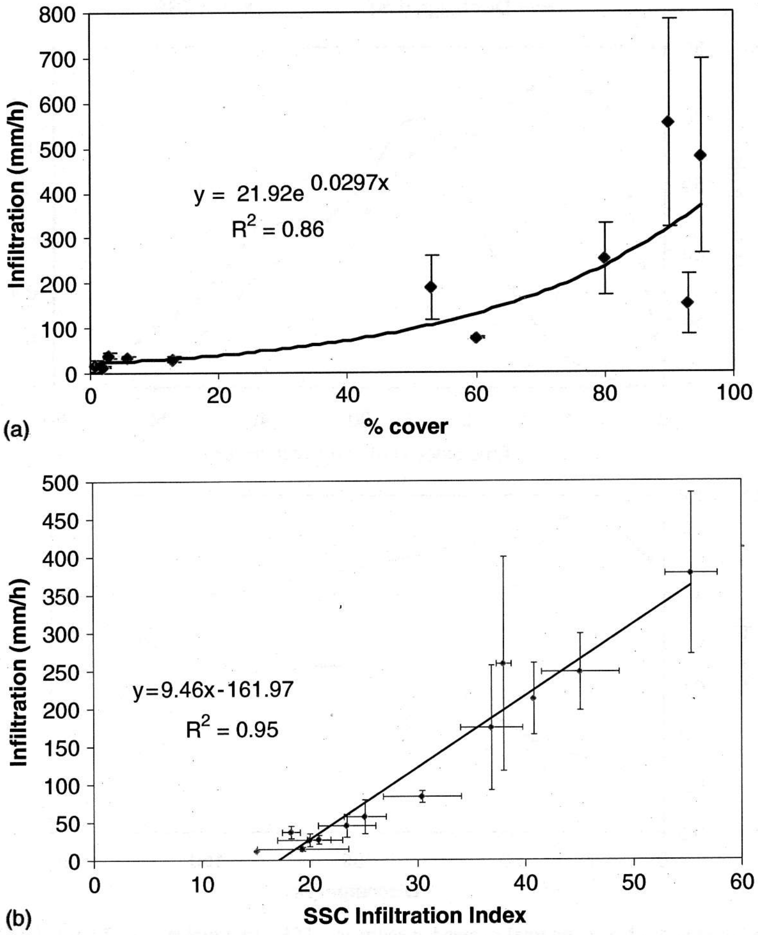

Figure 6. (a) Relationship between % cover and measured infiltration (mm/h). (b) Relationship between the soil surface condition (SSC) infiltration index (of Tongway and Hindley, 2004) and the measured infiltration rate (mm/h)

DISCUSSION

The difference in runoff ratio and soil loss from each of the flume sites cannot easily be attributed to differences in slope or slope length (see Table I). Nor can it be explained by differences in hillslope area in spite of the fact that the catchment area of Flume 1 is much larger than the other sites, and there is an increased opportunity for water and sediment storage. The main distinguishing factor between Flume 2 and Flume 3 is the location of an actively eroding patch just upstream of the flume in Flume 3. This bare patch was considered to be generating most of the runoff and sediment at the site. This hypothesis is supported by an analysis of individual flow events that show that in instances where there is no flow from Flume 2, runoff was still recorded from Flume 3, with particularly high TSS, indicating the bare patch as being the source of runoff. It also coincides with a more erodible soil that is highly dispersive because of the sodic nature of its B-horizon, which has been fully exposed. Thus, average cover values alone without taking into account the spatial distribution of patches and their interaction with changes in soil characteristics, are not capable of explaining the differences in runoff and sediment yield at the hillslope scale.

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This study also highlights that you may get significantly different results depending not only on the spatial distribution of the patches on the entire hillslope, but the spatial distribution of the patches relative to where the measurements are made (i.e. the flume). In previous studies of this type, it may be that researchers avoided, rather than included bare patches in their runoff studies; if they were included they may not have been located at the bottom of the hillslope.

In the case of Flume 1, given the overall higher cover levels (Table II), one could expect lower runoff and sediment yield when comparing Flume 1 to Flume 2. In this case, there are two factors contributing to the higher runoff ratios and sediment yields from Flume 1. In contrast to Flumes 2 and 3, which have similar planar hillslope topography, the micro-catchment of Flume 1 is characterized by a distinct thalweg (Figure 2(a)), leading to concentration of flow, as evidenced by the higher peak runoff rates (Table III) in comparison to Flume 2. In addition, there is a bare patch located slightly higher upslope with respect to the flume (Figure 2(a)). Both are factors thought to be contributing to higher sediment generation and transport. While it shows that the location of patches is an important factor; it also suggests that hillslope topography plays an important role in hillslope hydrology.

Other studies have noted that the magnitude of the events, in terms of rainfall intensity, can override any influence of cover. For example, McIvor *et al.* (1995b) suggested that in very large events (e.g. >45 mm/h) cover has no effect on runoff volume. The results from this flume study, however, suggest that there is no consistent relationship between the peak rainfall intensity and peak runoff rate for any of the flumes. This is because there appears to be a suite of factors, other than rainfall intensity and cover, interacting at the hillslope scale. Some factors that may influence hillslope runoff at the seasonal scale include the antecedent SSCs, surface sealing, the presence of swelling clays, sub-surface flow, A-horizon depth variation, earthworm and macropore presence.

As well as the bare patches contributing to excess runoff and soil loss, an important observation is the fact that the grassed patches down slope of the bare patches on Flumes 1 and 2 appear to be trapping fine sediment; this is most obvious when comparing the fine soil loss for the three flumes (Table IV). The fine soil loss is up to 40 times lower from Flume 2 (2004 data) and 30 times lower from Flume 1 (2005 data) than for Flume 3. Both Flumes 1 and 2 have low cover patches located on their hillslopes, but they are located further upslope away from the flume (see Figure 2(a) and (b)). Therefore, it appears that the fine sediment that is being lost from these bare patches has either adhered to the roughness (vegetation and soil) down slope, or the soil has been drawn into the soil matrix via macropores with the infiltrated runon.

Consistent with the higher runoff coefficient observed in Flume 3, overall sediment yield was also about an order of magnitude higher when compared to Flumes 1 and 2. It appears that the greatly increased bedload component for Flume 3 in 2004 (49·1%, Table IV) might be due to the significantly higher peak runoff rate observed (51 mm/h, Table III). However, Flume 1 also had a similarly high peak runoff rate in 2004 (60 mm/h, Table III), but the bedload component remained extremely small. We suggest this may also be due to a greater degree of bedload trapping by the well covered patch downslope of the bare patch and just upslope of the flume throat (Figure 2).

More generally, the degree to which sediment yield is dominated by suspended sediments (Table IV), in particular in Flumes 1 and 2, was a somewhat unexpected result, although the absolute soil loss data for these two flumes compares well with data collected by Roth *et al.* (2003) and O'Reagain *et al.* (2005) who measured sediment yield from similarly sized hillslope micro-catchments in other watersheds of the Burdekin basin. A number of possibilities exist to explain this behaviour. It is possible that we have underestimated bedload, as the bedload traps may have been under designed for some of the large flow events. However, even if we had underestimated bedload by an order of magnitude, TSS to bedload ratios would still be very high. A more likely explanation is that the highly eroded hillslopes of the Granodiorite landscapes in the Burdekin catchment have been largely stripped of their more erodible, sandy loam to loamy sand A-horizons (Table I), and that the progressively exposed clay subsoils have a greater resistance to particle detachment than the A-horizon. This hypothesis is in part supported by the visual evidence of the dark red B-horizon determining the colour of the surface and the absence of any thicker layers of sandier material on the hillslope

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areas, and the high concentration of suspended sediments that can be generated on bare patches (Figure 4). These results are similar to those of Scanlan *et al.* (1996) that found as cover increased, suspended sediment became a greater proportion of the total soil movement.

The results of this study also suggest that measured soil loss from hillslopes in the Burdekin Catchment is considerably less than those estimated using large scale catchment modelling. For example, Prosser *et al.* (2002) suggest that average soil erosion in the Burdekin Catchment is ~9·5 t ha^{-1} yr^{-1}. This is more than three times the maximum soil loss measured for Flume 3. It is important to remember, however, that the results from this study are based on three below average rainfall years. In fact, the 3-year average rainfall experienced at the flume sites over the study period is less than half the long term average for the area (based on the 598 mm/yr^{-1} at Fanning River Station). This would suggest that if 'average' or cyclonic rainfall conditions occur at the study site, both the water and sediment yields for all three flumes could increase considerably, and be more comparable with the results from Prosser *et al.* (2002).

When runoff is evaluated at the 'event' scale, a strong 'first flush' process is evident suggesting that cover levels at the beginning of the wet season are important for controlling water and sediment loss from grazed hillslopes. When water and sediment yields are evaluated at longer time scales (e.g. annual average time scales) it is important that this process is accounted for, otherwise there is the potential to underestimate the sediment yields from hillslopes using annual average data alone.

It is acknowledged that sediment yield generally declines with increasing scale (Schumm, 1977), however, this study has shown that at the hillslope level, the spatial arrangement of vegetation may, in some cases, override the effects of increasing spatial scale. This occurs because relatively small areas, if severely disturbed, can form large bare patches and then even rills and gullies, resulting in much higher sediment losses per unit area than a larger sized plot with high cover. This inverse relationship between runoff and scale was also acknowledged by Wilcox *et al.* (2003).

At the hillslope scale (>2000 m^2), the mozaic and interaction of patch types overrides any 'average' value of cover. Therefore using approaches such as semi-variance and autocorrelation techniques (Boer and Puigdefabregas, 2005; Northup *et al.*, 2005) may be more suitable for describing the spatial arrangement of vegetation in these patchy landscapes. These indices may then be better correlated with runoff and sediment loss from hillslopes in semi-arid areas.

Results presented in Figure 6 indicate that infiltration at the point scale shows some analogies with runoff generation at the hillslope scale. Taking cover as the sole predictor of infiltration is not as robust as relating infiltration (and hence runoff generation) to characteristics such as bioturbation and SSC, just as runoff and sediment yield at the hillslope scale cannot be fully interpreted using average cover on its own.

In summary, the amount and arrangement of ground cover is considered to be an important variable influencing the movement of water and soil from hillslopes in savanna regions. In this study we found that the arrangement of cover on a hillslope, and in particular the location of low and high cover patches, is more important than the 'average' cover condition. This seems to also be true of patches at the point scale, where cover needs to be augmented with information on surface condition. The results in this study do not necessarily support other studies that suggest that increasing cover, decreases water and sediment yield (e.g. McIvor *et al.*, 1995b; Scanlan *et al.*, 1996). In fact, in this study, the site with the highest 'average' cover has the highest water and sediment loss. The results suggest that small patches of bare ground within a relatively well covered hillslope can produce disproportionately high runoff and sediment loss, and the closer those patches are to the bottom of the hillslope the lower the opportunity for trapping/storage, and therefore the greater the opportunity that these resources are lost to the stream network.

Future work will be focused on trying to reproduce the measured data presented in this paper within a modelling context. A number of methods will be investigated including the use of runoff routing models specifically designed for savanna areas (e.g. 'Savanna.au'; Coughenour, 1993; Liedloff *et al.*, 2001). If a hillslope model can be adequately calibrated it will then be possible to run scenarios of different cover

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arrangements to demonstrate the influence of bare patches on water and sediment yields for different locations on a hillslope.

CONCLUSIONS

This paper utilizes the existing literature to highlight the relevant issues influencing the amount and arrangement of ground cover in savanna rangelands in Australia, including grazing, introduced pastures and weeds, fire and tree clearing. The study then demonstrated how sites with the same mean vegetation cover and hillslope characteristics can have very different water and sediment yields depending on the arrangement of the cover patches on the hillslope. Hillslopes with relatively high mean cover, but with small patches bare of vegetation can have between 6 and 9 times more runoff, and up to 60 times more sediment loss than similar hillslopes that do not contain large bare patches. This finding has important implications for grazing management and highlights how areas of low or no cover can have a significant influence on the overall water and soil loss from a hillslope. It is of even more significance when these bare patches are located at the bottom of hillslopes as the opportunity for trapping and storage is reduced and therefore the loss from the hillslopes to the stream network is increased.

This investigation also demonstrated that large proportions of soil loss can occur during the initial runoff events, and for these early 'first flush' events, the amount of soil loss appears to be relatively independent of the amount of runoff. This highlights how important it is to have adequate ground cover on grazed hillslopes at the end of the dry season when the early wet season storms are prevalent.

The generally lower than expected sediment yields from these plots may be illustrating that hillslope erosion is not necessarily the dominant source of sediments in these grazed savanna landscapes, and in fact, bank and gully erosion may be playing a more significant role than first considered. More hillslope data from 'average' rainfall years and data on bank and gully erosion rates will be needed to verify this observation. Either way, maintaining good ground cover on hillslopes is important for reducing sediment loss from hillslopes as well as reducing runoff that impacts on gully and stream bank erosion.

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