Journal of Hydrology 389 (2010) 237–248

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Impacts of improved grazing land management on sediment yields, Part 1: Hillslope processes

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ARTICLE INFO

Article history:
Received 17 September 2009
Received in revised form 1 March 2010
Accepted 1 May 2010

This manuscript was handled by G. Syme, Editor-in-Chief

Keywords:
Great Barrier Reef
Soil erosion
Grazing
Runoff
Sediment

SUMMARY

Poor land condition resulting from unsustainable grazing practices can reduce enterprise profitability and increase water, sediment and associated nutrient runoff from properties and catchments. This paper presents the results of a 6 year field study that used a series of hillslope flume experiments to evaluate the impact of improved grazing land management (GLM) on hillslope runoff and sediment yields. The study was carried out on a commercial grazing property in a catchment draining to the Burdekin River in northern Australia. During this study average ground cover on hillslopes increased from ~35% to ~75%, although average biomass and litter levels are still relatively low for this landscape type (~60 increasing to 1100 kg of dry matter per hectare). Pasture recovery was greatest on the upper and middle parts of hillslopes. Areas that did not respond to the improved grazing management had <10% cover and were on the lower slopes associated with the location of sodic soil and the initiation of gullies. Comparison of ground cover changes and soil conditions with adjacent properties suggest that grazing management, and not just improved rainfall conditions, were responsible for the improvements in ground cover in this study. The ground cover improvements resulted in progressively lower runoff coefficients for the first event in each wet season, however, runoff coefficients were not reduced at the annual time scale. The hillslope annual sediment yields declined by ~70% on two out of three hillslopes, although where bare patches (with <10% cover) were connected to gullies and streams, annual sediment yields increased in response to higher rainfall in latter years of the study. It appears that bare patches are the primary source areas for both runoff and erosion on these hillslopes. Achieving further reductions in runoff and erosion in these landscapes may require management practices that improve ground cover and biomass in bare areas, particularly when they are located adjacent to concentrated drainage lines.

1. Introduction

Livestock grazing is Australia's largest land use occupying 58% of the continent (www.brs.gov.au/landuse). In many grazing areas poor land condition, resulting from unsustainable grazing practices, has reduced the productivity of land for beef production and increased water, sediment and nutrient yields leaving the landscape (e.g. Bartley et al., 2007; McKeon et al., 2004). Evidence suggests that excess sediments and nutrients can also impact on the water quality and ecology of adjacent rivers and streams (e.g. McIver and McInnis, 2007; Vidon et al., 2008) and downstream ecosystems such as the Great Barrier Reef (GBR) (Fabricius, 2005; Fabricius et al., 2005; McCulloch et al., 2003).

Sediments are delivered to streams from three main sources (hillslope, gully or bank erosion). Hillslope erosion is the source that has received the most attention in the last decade in rangeland regions of northern Australia (e.g. Bartley et al., 2006; McIvor et al., 1995; Scanlan et al., 1996), and internationally it is also well researched (e.g. Branson et al., 1972; Stone et al., 2008). Trimble and Mendel (1995) provide a thorough review on the range of impacts that grazing and cattle can have on catchment processes including soil hydrology, hillslope runoff, bank erosion and stream channel structure. Whilst previous studies have described the degradation process, few have looked at land condition recovery and subsequent water quality changes following cattle exclusion or reduction. For the few international studies that describe the changes (or improvements) to water quality following cattle removal from pastures and/or riparian areas, the rates of this change vary considerably from 2.5 to 10 years for phosphorus and sediment loads (e.g. Bishop et al., 2005; Ellison et al., 2009; Line

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0022-1694/$ - see front matter
doi:10.1016/j.jhydrol.2010.05.002

et al., 2000) to between 3 and 13 years for hillslope hydrology (e.g. Branson et al., 1981; Sartz and Tolsted, 1974).

In Australia, previous studies have evaluated whether changes to land management affect ground cover and land condition, particularly in a historical context (e.g. Ash et al., 2001; Bastin et al., 2001; McKeon et al., 2004), and a recent study found that sediment yields from hillslope plots were reduced by 50% after one year of cattle exclusion (Hawdon et al., 2008). Most of these studies were undertaken under controlled conditions involving exclosures or complete cattle removal (McIvor et al., 1995; Scanlan et al., 1996), and there are no known studies that have been carried out under commercial grazing conditions. Given the importance of grazing to the Queensland and Australian economies (Gordon, 2007), there is a need to understand how improved grazing management, rather than livestock exclusion, can improve land condition and potentially improve downstream water quality.

The primary focus of grazing land management (GLM) in rangelands is vegetation management (Ash et al., 2001). There are four principal ways to rehabilitate or prompt recovery in rangeland vegetation: (i) reduce livestock density or utilisation (with or without seasonal pasture resting), (ii) prescribed burning, (iii) sowing introduced plant species and (iv) reseeding native plant species (Noble et al., 1984). Utilisation is defined as the proportion of pasture growth consumed over a year (Ash et al., 2001). These methods are considered in the context of livestock production and may not necessarily be suitable for ecological management and restoration of vegetation communities.

In December of 2002, GLM strategies in the form of reduced utilisation and rotational wet season resting were implemented on Virginia Park cattle Station, in the Burdekin River catchment on Australia's east coast. This paper demonstrates how these improved grazing management strategies changed ground cover condition and associated water and sediment loss at the hillslope scale (~2030–12,000 m^2) over a 6 year period. The effect of this improved management on water and sediment yields at the catchment or property scale (14 km^2) is presented in (Bartley et al., 2010).

2. Study area

This study was carried out in the Weany Creek catchment (S19°53′06.79″, E146°32′06.65″), which is dominated by Eucalypt savanna woodland. The catchment is contained within Virginia Park station which is a privately owned cattle grazing property. The area is representative of the highly erodible 'gold-fields' (granodiorite) country between Townsville and Charters Towers in North Queensland, Australia, and has been grazed for more than 100 years. Weany Creek is an ephemeral 14 km^2 catchment of the larger Burdekin catchment (~130,000 km^2; Fig. 1). The Weany Creek catchment was chosen for this study due to its location in an area identified as having high erosion rates (Prosser et al., 2001), and due to the willingness of the landholders to trial sustainable grazing practices.

The soils in the catchment are generally Red Chromosols on the upper slopes and Yellow to Brown texture contrast soils with dispersive, natric B-horizons on the lower footslopes. Large bare scald patches are present on the slopes adjacent to many gully and stream networks. Scalds have formed on unstable duplex soils where the clay fraction of the sub-soil is high in sodium (Pressland et al., 1988). Long term overstocking on these soils has denuded the pasture, removed the A-horizon, and exposed the dispersible sub-soils along most of the drainage lines in this catchment.

The canopy vegetation is composed primarily ironbark/bloodwood communities (e.g. narrow-leafed ironbark, *Eucalyptus crebra* and red bloodwood, *Corymbia erythrophloia*) which are located primarily on the mid and upper slopes. The lower slope sodic soil communities are dominated by more shrubby species (e.g. currant bush, *Carissa ovata* and false sandalwood, *Eremophila mitchellii*). The ground cover is dominated by the exotic, but naturalised stoloniferous grass Indian Couch (*Bothriochloa pertusa*). Native tussock grasses such as Desert Blue grass (*Bothriochloa ewartiana*), Black Spear grass (*Heteropogon contortus*) and Golden Beard grass (*Chrysopogon fallax*) are present. Surveys of pasture composition over the study period show that native tussock grasses represent between 5% and 30% of total biomass depending on the paddock and year.

A map of the Virginia Park property and the location of the four study paddocks located within the Weany Creek catchment are shown in Fig. 2. It is important to point out that this grazing trial was initiated during a drought, on a property with generally low ground cover that was dominated by Indian Couch (>85% of total biomass). The ground cover and pasture biomass levels at the beginning of this project were on average ~63% and ~350 kg of dry matter per hectare (DM/ha), respectively. These values were well below what is considered 'sustainable' in terms of long term grazing management for this soil type (Ash et al., 2001).

There was a steady increase in the annual rainfall totals at Virginia Park between 2003 and 2007. With the exception of the 2006 and 2007 wet seasons all years were under the long term average (1901–2006) for nearby Fanning River rain gauge of ~584 mm

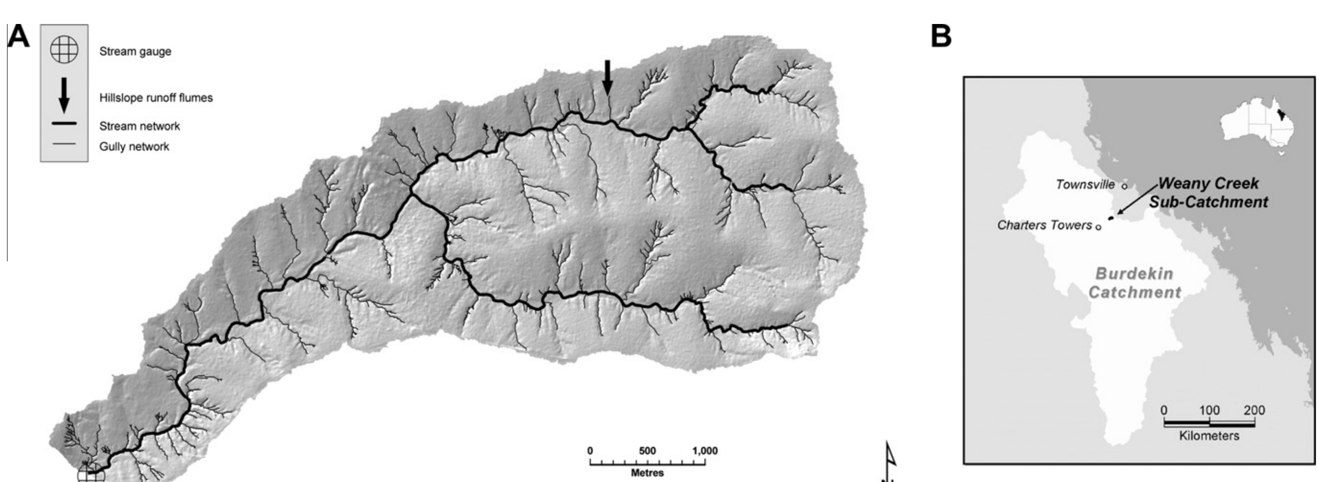

Fig. 1. (A) The Weany Creek catchment showing the stream and gully network and the location of field monitoring sites. The catchment outlet is in the southwest corner. (B) The location of the study catchment within the Burdekin River catchment.

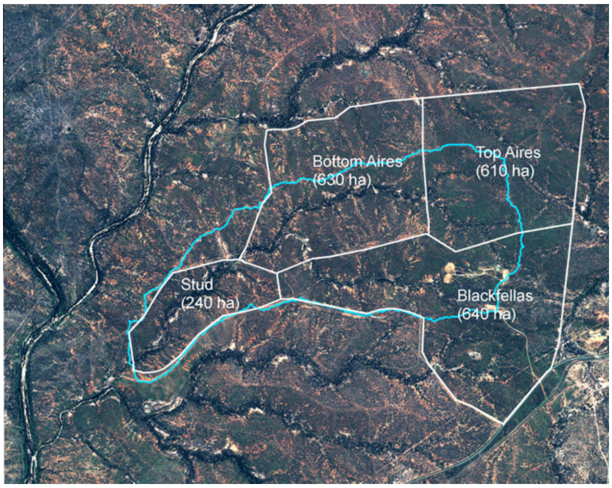

Fig. 2. Study location showing the Weany Creek catchment boundary (blue line) and the paddock boundaries on Virginia Park Station (white lines). The background is a pan-sharpened real-colour image derived from the Quickbird™ satellite, taken in December 2003. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(http://www.nrm.qld.gov.au/silo) (Table 1). The flume data is presented according to the year the wet season started (e.g. the wet season that started in 2002 and ended in 2003 is called 2002). Most of the rain falls between December and April each year but occasionally out of season events occur and therefore the hydrology data extends from July 1st to June 30th each year.

3. Methods

3.1. Grazing and pasture management strategy

The two primary management practices implemented as part of the adaptive management GLM strategy in this study included (i) reduced utilisation achieved by adjusting cattle numbers and (ii) wet season resting in alternate years. In this study utilisation rates were applied based on standing dry matter using the methods described in Post et al. (2006). Wet season resting allows pasture to take advantage of summer rain without grazing (Ash et al., 2001).

Estimated stocking rates for the study paddocks over the past two decades were approximately 1 beast to 4 ha, although actual utilisation rates varied with seasonal conditions. At the beginning of the study ~200 head of cattle were removed from the property and agisted elsewhere for 4 years. This reduced the pre-trial stocking rate by ~60%, and from 2003 to 2006 the stocking rates averaged to 1 beast to 10 ha. It is important to note that de-stocking was part of the adaptive management strategy used in response to the severe drought in 2003. De-stocking is not a common component of GLM for non-drought conditions in this region. Due to the drought conditions in 2003 all four study paddocks were de-stocked for approximately 3 months to help pasture recover from extremely low levels. Stock were reintroduced to these paddocks in July 2003. The timing of wet season resting is given in Table 1.

The intended outcome of the combination of reduced utilisation and resting was to achieve minimum residual yields of 400 kg of dry matter per hectare (DM/ha) (<35% use of standing dry matter) in Top Aires and Blackfellas paddocks. Bottom Aires Paddock was stocked to obtain a minimum residual yield of 500 kg DM/ha (<35% use of standing dry matter). The aim was to have 40% ground cover at the end of the dry season in all paddocks. Stud Paddock was set up to receive annual wet season rest, however, as it was very small, it was used temporarily during the wet season as a holding paddock. Less than 50% of the standing dry matter was used during the study.

The sustainable grazing treatments formally ended in June 2006 (with the end of project funding for cattle agistment). The owners of Virginia Park station have, for the most part, continued moderate stocking and wet season resting regimes until June 2008. Further details of the stocking rates, pasture utilisation and forage budgeting methods are given in Post et al. (2006).

3.2. Hillslope monitoring sites at Virginia Park Station (Weany Creek catchment)

To quantify the linkage between pasture management, land condition and water and sediment loss at the hillslope scale, three hydrological flume hillslope sites were established in 2002. Water movement via sub-surface flow was not considered to be a major flow pathway in these semi-arid headwater environments, and it was not needed for estimating soil erosion; therefore sub-surface flow was not monitored. The hillslope flumes are located within 400 m of each other in the Bottom Aires paddock (Figs. 1 and 2). There are considerable variations in ground cover pattern within and between the flume hillslopes. There are also differences in vegetation communities between the upper and lower areas of individual hillslopes. The upper and middle slopes are dominated by ironbark/bloodwood with Indian Couch as the dominant grass. The lower slopes have patches of shrubby vegetation (e.g. *Carissa*) often on or adjacent to exposed sodic soils that have little or no grass cover.

In an attempt to capture the different spatial patterns of vegetation, each hillslope has a different vegetation configuration. The Flume 2 catchment, located in the mid-upper hillslope sections, had a fine-grained vegetation arrangement with no large bare patches. The Flume 1 catchment, occupying almost the entire hillslope catena, is medium-grained with a number of bare patches (<6 m^2) and some areas of moderate to high cover, especially in lower slope locations. The Flume 3 catchment, occupying most of the hillslope, has a coarser-grained patch arrangement with a large scald or bare patch at the base of the hillslope (>6 m^2) and a finer-grained patch arrangement with moderate to high cover at the top of the hillslope (Fig. 3). Despite the differences in vegetation pattern, each of the flumes had very similar 'average' ground cover at the beginning of the study (see Tables 2–4).

To determine the area, slope and topography of each flume, the sites were surveyed at approximately 4 × 2 m spacings using a Wild TC 1000 total station. The data were then converted to a DEM profile using TOPOGRID within ArcInfo. The hillslope catchment of Flume 1 is ~11,930 m^2 with a mean slope of 3.9% and slope

Table 1
Annual rainfall (measured at Flume 1) and timing of wet season resting in each paddock during the study.

Paddock	2002–2003	2003–2004	2004–2005	2005–2006	2006–2007	2007–2008
Rainfall (mm)	304	245	382	457	706	760
Top Aires	Wet rest		Wet rest		Wet rest	Wet rest
Bottom Aires		Wet rest	Wet rest		Wet rest	Wet rest
Blackfellas		Wet rest		Wet rest		

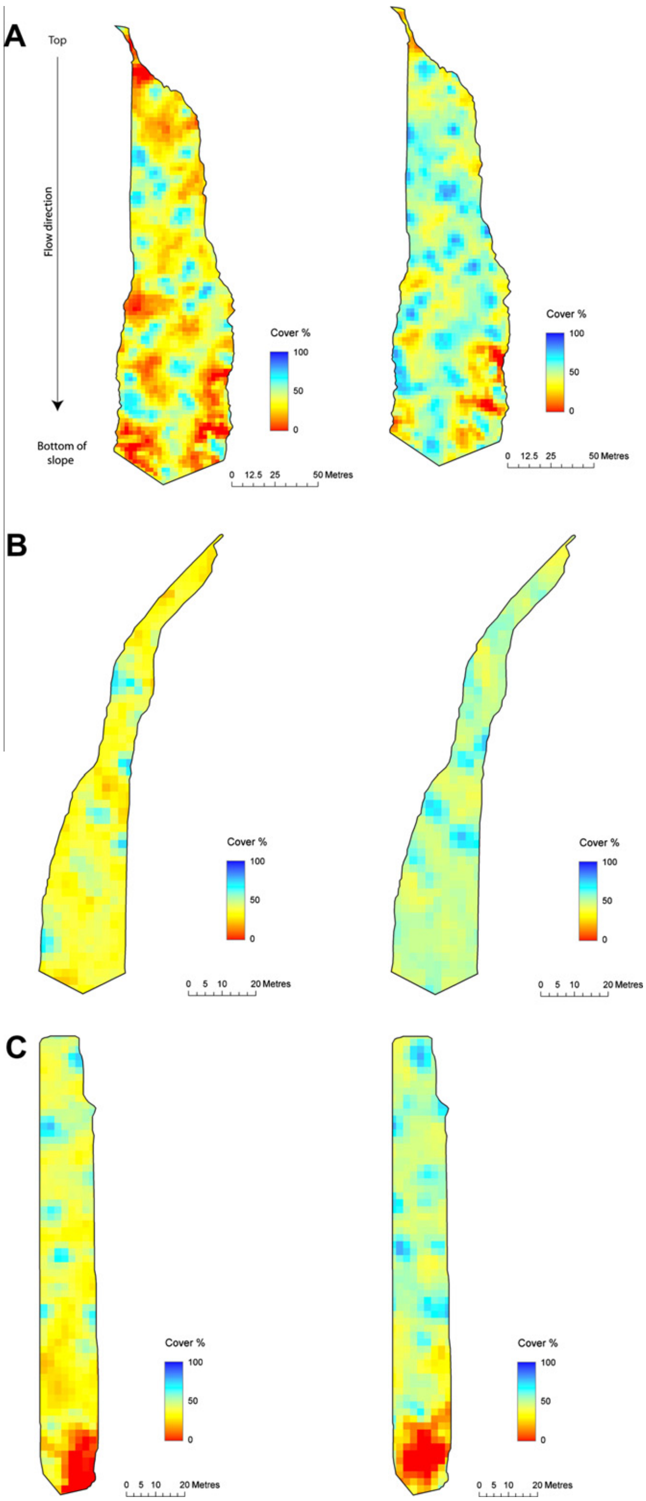

Fig. 3. Quickbird derived cover (%) on each of the three hillslope flume sites in 2003 (left) and in 2007 (right). (A) Flume 1, (B) Flume 2 and (C) Flume 3. Flow direction is downwards in all images. Note the scale differences between Flumes 1, 2 and 3. Quickbird imagery was not available for the beginning of the study in 2002.

length of 240 m. A drainage line runs down the centre of the lower half of the Flume 1 catchment, where upslope sheet flow becomes channelized during intense rainfall. The low cover areas are on the side edges of this hillslope catchment, and are not well connected to the drainage line. The Flume 2 catchment area is ~2031 m^2, with a slope length of 130 m. It is located ~120 m upslope from the main creek line in the catchment and has a relatively uniform gradient (mean slope of 3.1%), with no drainage line. Runoff moves as sheet flow across this hillslope. Flume 3 has a catchment of ~2861 m^2 with a mean slope of 3.6% and length of 150 m. While Flume 3 does not have a distinct drainage line, there are rill features on the bare soil located on the lower slopes (see images in Bartley et al., 2006). Flume 3 is located higher on the hillslope than Flume 1, but runoff from the bottom of the catchment drains into a small gully network, with the gully head being approximately 10 m down-slope from the flume outlet, and ~0.5 m in depth. For more detail on the hillslope instrumentation see Bartley et al. (2006).

Table 2
Cover attributes for Flume 1 (2002–2007). Standard error (SE) in brackets.

Year	Field data		Quickbird data
	Average cover (%) (SE)	Pasture biomass (kg DM/ha dry matter) (SE)	% of land with <10% ground cover
2002	61.5 (0.8)	347.4 (6.9)	–
2003	33.8 (0.3)	59.3 (4.0)	7.5
2004	44.3 (1.1)	239.6 (14.1)	3.2
2005	57.2 (1.1)	521.3 (17.9)	3.6
2006	71.7 (1.2)	914.5 (44.4)	1.2
2007	71.6 (1.2)	983.7 (39.0)	1.5

Table 3
Cover attributes for Flume 2 (2002–2007). Standard error (SE) in brackets.

Year	Field data		Quickbird data
	Average cover (%) (SE)	Pasture biomass (kg DM/ha dry matter) (SE)	% of land with <10% ground cover
2002	58.0 (0.9)	392.6 (13.9)	–
2003	37.9 (0.5)	62.1 (3.2)	<1
2004	34.1 (1.8)	153.0 (12.3)	<1
2005	50.2 (1.8)	478.5 (22.3)	<1
2006	74.1 (2.4)	782.2 (39.5)	<1
2007	76.3 (1.5)	1123.2 (75.3)	<1

Table 4
Cover attributes for Flume 3 (2002–2007). Standard error (SE) in brackets.

Year	Field data		Quickbird data
	Average cover (%) (SE)	Pasture biomass (kg DM/ha dry matter) (SE)	% of land with <10% ground cover
2002	68.1 (1.3)	321.4 (7.5)	–
2003	45.6 (1.0)	61.0 (3.5)	7.7
2004	46.6 (1.4)	145.5 (10.5)	6.7
2005	54.4 (2.1)	510.3 (23.3)	6.7
2006	72.7 (2.7)	667.3 (38.5)	5.3
2007	74.9 (1.8)	972.2 (47.0)	7.0

3.2.1. Hillslope ground cover and condition monitoring

Flume hillslope ground condition was measured using end of dry season surveys across each hillslope on an 8 × 4 m grid. At each grid point, pasture condition metrics were recorded across a 1 m quadrate, including the main species and/or functional group composition and frequency, biomass, percentage ground cover, litter cover, basal-area class, defoliation level and key soil surface condition (SSC) metrics (as outlined in Tongway and Hindley, 1995). Information on vegetation/land type, landscape location and tree canopy cover was also recorded within a 10 m radius from each grid point. As well as on ground field measurements of cover, high resolution Quickbird satellite images with a 2.4 m^2 resolution (Pan sharpened to 0.6 m) were analysed for each of the hillslope flume sites for four out of the six years between 2003 and 2007. Appropriate Quickbird data were unavailable for 2002 and 2004.

3.2.2. Hillslope runoff and sediment yield monitoring

To measure water and sediment runoff, Flume 1 used a large Parshall flume for measuring high flows, and a combination weir for measuring low flows. Flumes 2 and 3 were 9 in. cut-throat flumes. Flume type was chosen to match potential runoff rates. It is acknowledged that there may be some bias in the results due to the different flume types used, however, this bias is considered minimal. Details of the data logger and associated instrumentation can be found in Bartley et al. (2006). An event was considered to occur when flow was greater than one L/s and there was more than 12 h prior without runoff. The % runoff for each event was calculated using the rainfall that fell during the period of event runoff. Annual % runoff was calculated as the total annual runoff divided by total rainfall for that water year. Maximum rainfall intensity during a 30 min (I_{30}) and 15 min (I_{15}) period were calculated for each event and for the whole season. Water sampling at Flume 1 was stratified by flow depth, and for Flumes 2 and 3 they were bulk samples up to 20 L, which were collected following major runoff events. All samples were analysed in the laboratory for EC, pH, turbidity, total suspended sediment (TSS) concentration and sediment particle size. TSS concentration was considered to represent the silt (0.002–0.063 mm) and clay (<0.002 mm) sediment fractions. Bedload samples (which were generally between 0.063 and 8 mm) were collected manually from bedload traps in each of the three sites and were assessed for mass and grain size distribution. When both concentration and discharge data were available, annual sediment loads were estimated by summing the event loads using the arithmetic mean approach (Letcher et al., 1999). When sediment concentration data were unavailable for an entire event, average values for that wet season were applied.

3.3. Data collection from Meadowvale Station

To investigate whether changes in flume runoff and sediment yield were due to changed pasture management or temporal changes in rainfall, hillslope runoff and total suspended sediment (TSS) concentration data were also monitored from 2002 to 2008 on a nearby property, Meadowvale Station (S19°50′30.67″, E146°35′19.81″). The Meadowvale Station sites are less than 20 km from Virginia Park Station, and have similar soils and landscape characteristics (Roth, 2004). At Meadowvale Station, two runoff troughs were situated in a grazing exclosure, which had no cattle grazing between 1986 and 1992, 'light' grazing between 1992 and 2002 (Alewijnse, 2003), and no grazing for 2002–2008 (Hawdon et al., 2008). A further two runoff troughs were situated outside the grazing exclosure. The Meadowvale hillslopes were slightly smaller than the Virginia Park flume sites (700–2600 m^2) but with similar slopes (3.5–4%). A total of 20 event bulk TSS samples were collected from the Meadowvale troughs from a range of events between 2001 and 2006. The water quality samples from Virginia Park and Meadowvale Stations were analysed at the same laboratory. A complete description of the Meadowvale Station site setup is given in Hawdon et al. (2008) and Scanlan et al. (1996). Average ground cover estimates for Virginia Park Station was also compared with that for a paddock on an adjacent property that had not undergone changed pasture management, presented in Bartley et al. (2010).

Grazing has been shown to have a significant impact on infiltration rates in rangelands (Gifford and Hawkins, 1978; Trimble and Mendel, 1995). To investigate the effect of light and heavy grazing practices on soil conditions, soil bulk density data collected on Virginia Park Station in 2004 (see Bartley et al., 2006) were compared with data from Meadowvale Station between 2000 and 2002. The Meadowvale Station soil samples were collected from sites that had undergone continuous grazing, sites within the grazing exclosure, and a site near the Meadowvale grazing exclosure, from which both cattle and kangaroos had been excluded for 16 years (Alewijnse, 2003). Saturated hydraulic conductivity at these sites was also measured using a hood infiltrometer using the methods described in Bartley et al. (2006). It is acknowledged that bulk density is a coarse surrogate for soil condition, however, other soil surface condition data (Tongway and Hindley, 1995) were unavailable for the Meadowvale site.

4. Results

4.1. Pasture and biomass change on the hillslope

For Flumes 1, 2 and 3, the change in cover (%), pasture biomass, and area of the hillslope with <10% cover are given in Tables 2–4, respectively. The % cover for each hillslope at the beginning (2002) and end of the study (2007) is shown in Fig. 3, demonstrating that the overall average % cover has increased on all of the hillslopes over the study period.

The magnitude of cover change was variable both within, and between, hillslopes, with upper parts of the slopes recovering better than lower parts. Most of the increase in cover on the upper slopes was caused by Indian Couch (*B. pertusa*) colonisation which increased by ~2.5 times between 2002 and 2007 on each of the flumes (Fig. 5A). The native perennial tussock grass yield was very low on all flumes at the beginning of the study, but increased by between 3 and 7 times by the end of the study (Fig. 5B). Areas immediately under or adjacent to live tree canopy had up to 20% more ground cover and over 100% more litter cover than areas away from tree canopy ($p < 0.005$). Areas under tree canopy also had up to 45% more pasture biomass than equivalent areas away from canopy, while frequency of native perennial grasses was 27% higher under tree canopy ($p < 0.005$). Litter contribution in non-canopy areas remained relatively low throughout the study, despite the increase in total ground cover in those areas (Fig. 4).

The biggest difference in cover change between Flume 1 and Flume 3 was in the proportion of area with low cover (<10% cover), as quantified using the Quickbird imagery (Fig. 6B). Flumes 1 and 3 initially started with similar amounts of low cover land in 2003. With the implementation of improved GLM the proportion of this land condition type reduced on Flume 1 but not on Flume 3. Most of the cover improvements occurred on the upper parts of the hillslopes and in areas that were not in the main flow path (Fig. 3). Large areas of low cover persisted at the base of hillslopes adjacent to gullies and stream lines (e.g. Flume 3).

4.2. Hillslope runoff and sediment yields

Flume 3 has consistently higher % runoff and sediment yield for the length of the study (Fig. 9A). Over the six year study Flume 3 on average, had 6 times more runoff and 88 times higher sediment yield than Flume 2, and 4.5 times more runoff and 27 times higher sediment yield than Flume 1. The % of rainfall that became runoff increased on Flumes 1, 2 and 3 over the 6 year study period (Figs. 7A, 8 and 9A), associated with higher annual rainfall in latter years.

Rainfall intensity (I_{15} and I_{30}) had little influence on the proportion of rainfall that became runoff for the 22 Flume 1 runoff events over the study period (Fig. 10A). Similarly, the amount of rainfall prior to a runoff event was not a strong predictor of runoff (Fig. 10B). A possible explanation is the large variation in the number of days over which rain fell (data not shown). For some runoff events, rainfall occurred over almost 3 months before any runoff

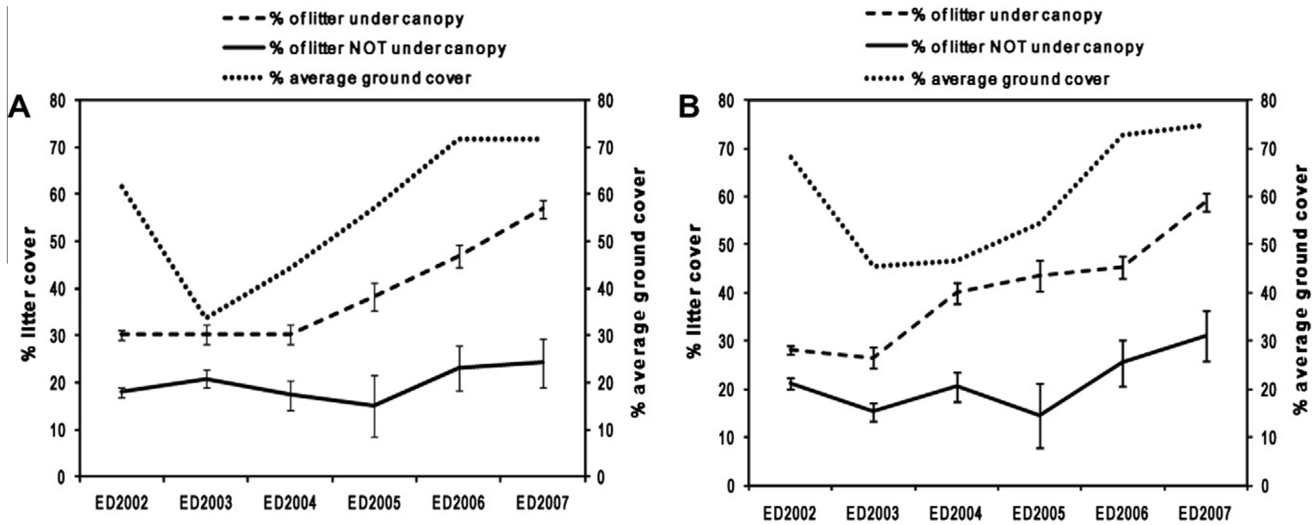

Fig. 4. Changes in the amount of litter on the hillslope compared to general ground cover for (A) Flume 1 and (B) Flume 3, shown with standard error bars. ED = end of dry season.

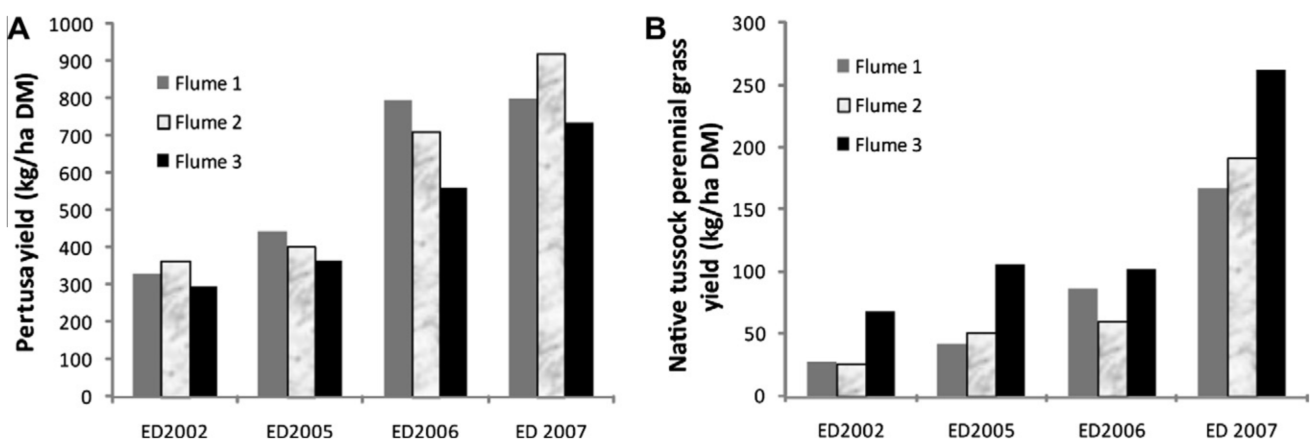

Fig. 5. Change in (A) Indian Couch (*Bothriochloa pertusa*) yield and (B) Native tussock perennial grass yield for each of the flumes from the beginning (2002) to the end of the study (2007). No pasture composition data were collected in 2003 and 2004.

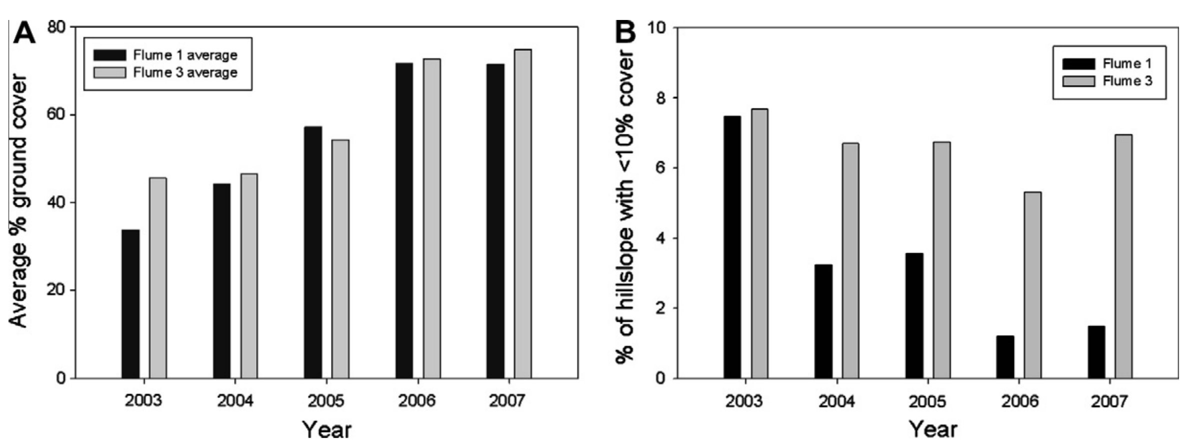

Fig. 6. (A) Average % ground cover on Flume 1 and 3 between 2003 and 2007 measured on the ground and (B) % of area with <10% ground cover on Flumes 1 and 3 between 2003 and 2007 measured using Quickbird imagery.

occurred. For other events, particularly those within hours or days of the preceding event, there was little or no preceding rain before runoff is initiated. Although the amount of rainfall preceding an event appears to have no influence on runoff, ~64% of the variability in Flume 1 runoff can be explained by the amount of rainfall during an event (Fig. 10B). At least for the first runoff events of

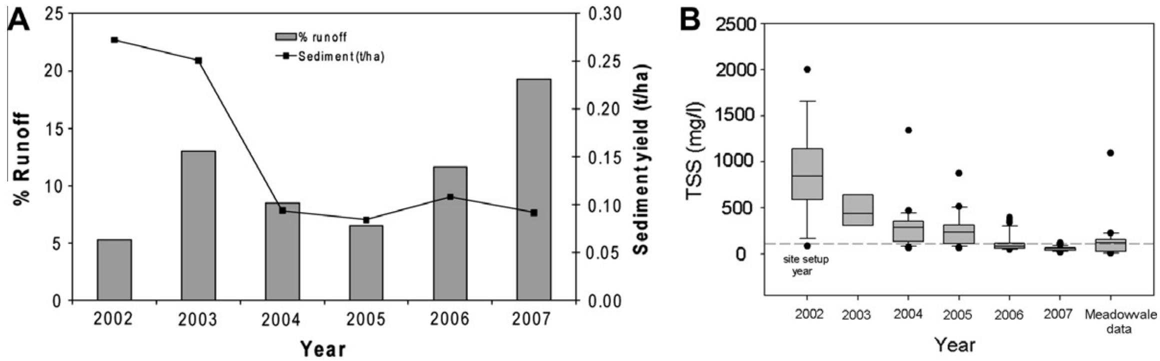

Fig. 7. (A) Changes in % runoff and sediment yield (t/ha) over the 6 year study period at Flume 1 and (B) total suspended sediment (TSS) values from Flume 1 compared with the Meadowvale data from the grazing exclosures described in Hawdon et al. (2008). The horizontal dashed line is the average of the Meadowvale data.

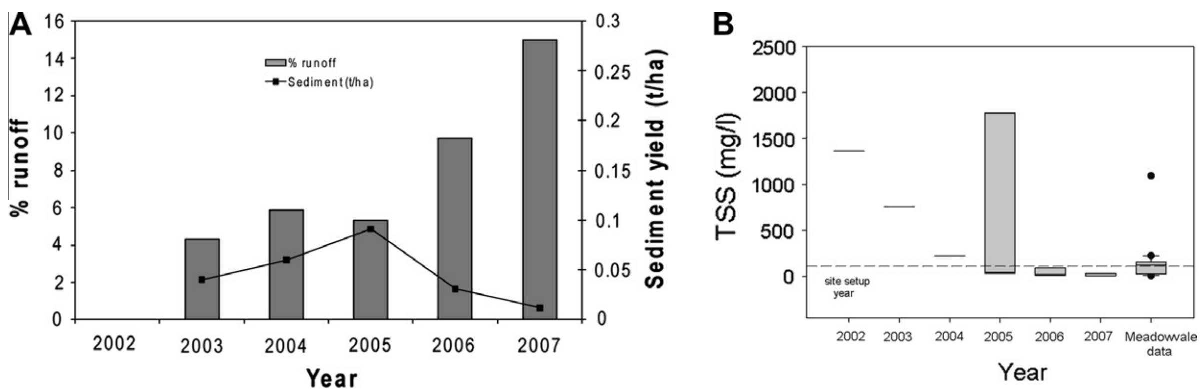

Fig. 8. (A) Changes in % runoff and sediment yield (t/ha) over the 6 year study period at Flume 2. Note that logger malfunction prevented accurate runoff and load data being calculated for 2002, but TSS samples were collected and (B) total suspended sediment (TSS) values from Flume 2 compared with the Meadowvale data from the grazing exclosures described in Hawdon et al. (2008). The horizontal dashed line is the average of the Meadowvale data.

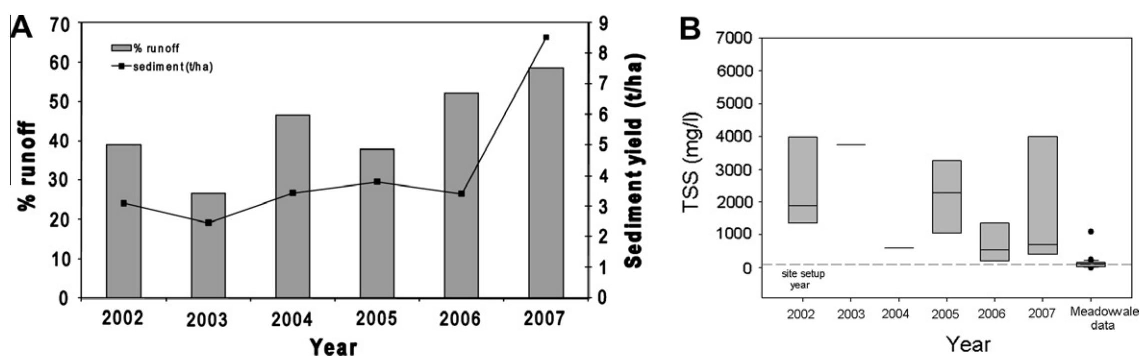

Fig. 9. (A) Changes in % runoff and sediment yield (t/ha) over the 6 year study period at Flume 3 (scald flume). (B) TSS values from Flume 3 compared with the Meadowvale data from the grazing exclosures described in Hawdon et al. (2008). The horizontal dashed line is the average of the Meadowvale data.

the season, the amount of biomass on the hillslope surface was an important driver of the amount of rainfall that became runoff (Fig. 10C). This response was stronger on Flume 1 than Flume 3. Changes between years in the amount of runoff from events early in each wet season can also be seen in Fig. 11.

Soil bulk density declines with reduced grazing intensity (Fig. 12). There appears to be a threshold soil bulk density of approximately 1.5 g/cm^3 below which infiltration increases considerably with further reductions in bulk density. At Virginia Park sites 95% of bulk density values were greater than 1.5 g/cm^3. These data were measured at the beginning of the 2004 wet season, which was in the height of the drought. No subsequent bulk density measurements are available.

Despite little change in the annual hillslope runoff coefficients over the 6 years of the study, there has been a decline in total sediment yields on two of the three flumes (Figs. 7–9). On Flumes 1 and 2, there was a 66% and 70% decline in sediment yield over the course of the study, respectively, (Figs. 7 and 8). As well a decline in total sediment yield, Flumes 1 and 2 also showed a decline in the mean TSS concentration over the 6 year study (Fig. 7B). The mean TSS concentrations collected at Flumes 1 and 2 in 2007 were not significantly greater ($p < 0.05$) than the mean TSS concentration at the Meadowvale cattle exclosure sites. Hence, the water quality coming off Flumes 1 and 2 in 2007 was equivalent to a site that has not been grazed for 5 years. At Flume 2, the first event in 2005 produced a very high sediment concentration (~1780 mg/l),

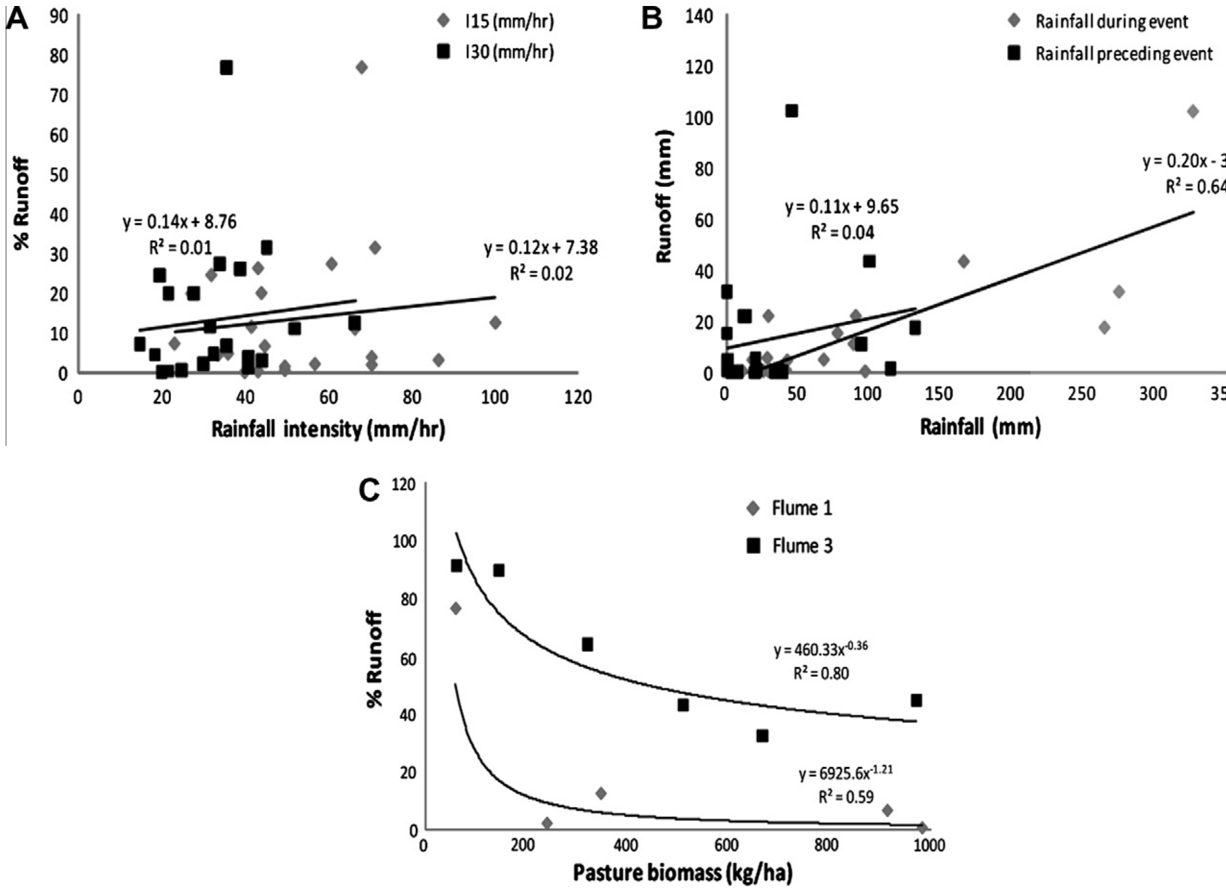

Fig. 10. (A) The relationship between rainfall intensity and event runoff for Flume 1, (B) rainfall and runoff (mm) for each of the 22 events measured at Flume 1 and (C) the influence of pasture biomass on the % runoff for the first event of each wet season for Flumes 1 and 3. Note that cover data are only available for the first events of the wet season.

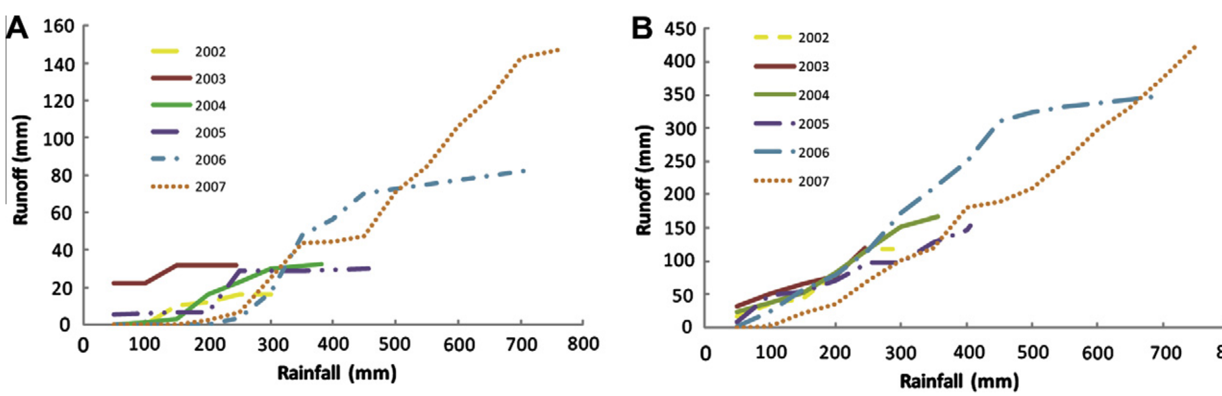

Fig. 11. Cumulative runoff (mm) against cumulative rainfall (mm) in each year, for (A) Flume 1 and (B) Flume 3.

however, the data were maintained as sub-soil ecological activity has been known to cause 'spikes' in sediment concentration data from hillslopes (McIvor et al., 1995), and therefore this value was considered to be within the range of natural variability. Ignoring the spike in 2005, Flume 2 followed the same sediment concentration decline as Flume 1. In contrast, Flume 3 sediment yield increased by 210% over the study period. The annual median TSS concentration for Flume 3 declined from 2002 to 2007, but the annual maximum TSS did not (Fig. 9B). While mean TSS concentration declined as cover increased on all of the flumes, the rate and amount of reduction was very different for Flumes 1 and 2 compared to Flume 3. Fig. 13A shows that as average hillslope cover increases beyond 60–70% on Flumes 1 and 2, TSS values are equivalent to the ungrazed TSS data from Meadowvale. On Flume 3, average ground cover across the flume catchment reached more than 70% yet TSS values remained very high. Hillslope TSS concentrations are greatly influenced by the proportion of hillslope area with <10% cover (Fig. 13B).

5. Discussion

5.1. The impact of grazing land management on vegetation

This study demonstrates that GLM, in the form of reduced pasture utilisation and wet season resting, can improve the average

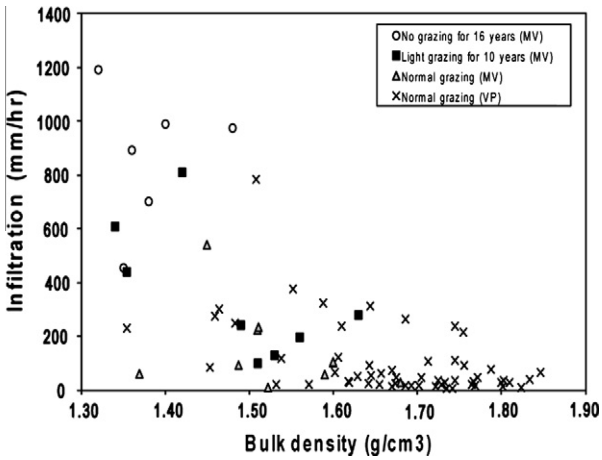

Fig. 12. Soil bulk density values and corresponding infiltration rates measured on a range of sites that have undergone different levels of grazing impact on Meadowvale Station (MV) and Virginia Park Station (VP) between 2000 and 2004.

ground cover on hillslopes from ~35% to 75% within 5 years of implementation. The recommended sustainable biomass for a commercial property in this land type (Goldfields country) is ~1700 kg DM/ha (Ash et al., 2001). Biomass levels increased dramatically during the study, up to 2200 kg DM/ha on some of the upper hillslope areas. However, average pasture biomass remained relatively low on hillslopes with patches of both high and low cover (~1000 kg DM/ha).

The study also finds that runoff and sediment yield are not well predicted by 'average' cover/biomass levels in this dry-tropics landscape. Spatial variability in cover and herbaceous biomass levels is considerable; in particular, this study demonstrates that areas where historical grazing has degraded pasture and caused high erosion are more susceptible to loss of cover in dry years, and that they respond much more slowly to improved GLM. Increasing ground cover on upper hillslope areas is likely to increase total biomass production there, but without improved cover on the highly erodible lower slopes, improvements to runoff quantity and quality are unlikely to be achieved at landscape scale. This finding supports previous findings that the size, number, location and interconnectedness or leakiness of patches, particularly the lower cover patches, is important to reducing runoff (Ludwig et al., 2006). We have found that improving GLM can reduce the size and abundance of low cover patches in the upper slope areas, however, large (>6 m^2) low cover patches at the base of hillslopes will need either more time, or more targeted interventions, for cover levels to increase.

This study has shown that increases in plant biomass resulted in only small increases in infiltration, restricted to rainfall events of small volume and intensity. While ground cover increased following the grazing management changes, the exotic stoloniferous grass Indian Couch continued to dominate the pasture (Fig. 5A). Therefore, it is likely that significant increases in soil infiltration rates, and consequent reductions in runoff coefficient at the annual time scale, will require further increases in the proportion of native tussock perennial grasses, and associated litter accumulation and soil fauna (Tongway and Hindley, 2004). Native tussock grasses provide the architecture to trap litter and sediment on hillslopes. Their root structure also provides deeper infiltration and nutrient storage than stoleniferous species (Jackson and Ash, 1998). For example, rainfall simulation experiments conducted on a range of tussock species (e.g. *H. contortus*) found infiltration down to 1 m below soil depth (Roth, 2004). Both the Indian Couch and native tussock grass yield did increase considerably during this study (Fig. 5), however, this recovery is considered fragile. A return to increased stock numbers and no wet season resting could easily return these hillslopes to pre-study conditions and jeopardise the full recovery of these sites. Given that biomass levels were very low in 5 out of the 7 years, further reductions in grazing pressure may be required to enable additional increases in biomass and the proportion of native pasture species.

5.2. The impact of grazing land management on hillslope hydrology and sediment yields

The annual runoff coefficients for Flume 3 (26–58%) appear high, although similar values have been observed in other studies (e.g. Girmay et al., 2009; Slattery et al., 2006). The dominant runoff mechanism in semi-arid systems is infiltration-excess runoff (Dunne, 1978). Infiltration-excess runoff is greatest when rainfall intensities are high and/or where the soil infiltration capacity is reduced due to surface sealing or low vegetation cover. Such runoff is controlled primarily by the infiltration characteristics, rather than the storage capacity, of the soil (Wilcox et al., 2003). The high runoff coefficients for Flume 3 are strongly influenced by the bare patch at the bottom of the hillslope. The annual runoff generated from Flume 3 is between 4 and 23 times higher than at Flume 2 (depending on the year). The top three quarters of Flume 3 has very similar surface area and slope to Flume 2. Assuming that Flume 2 is

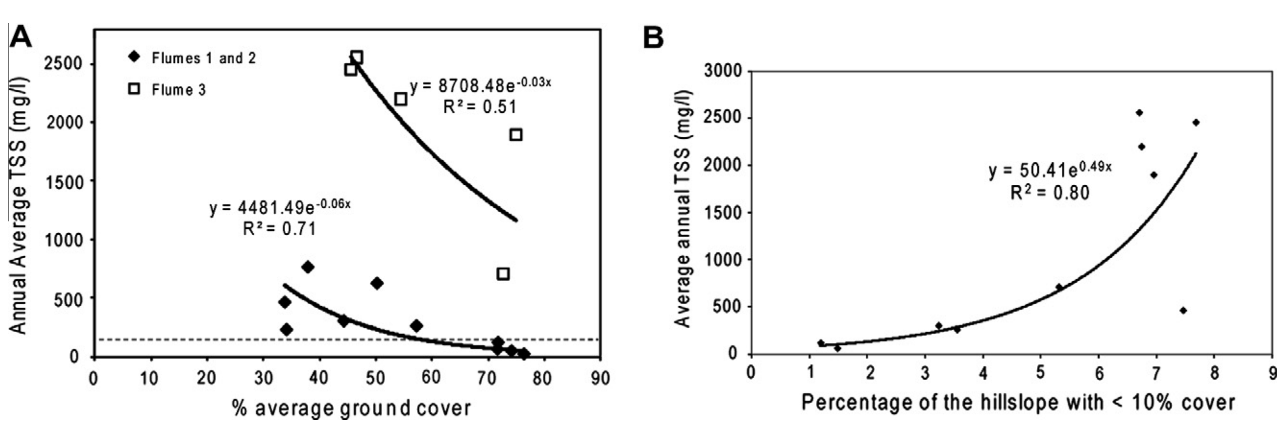

Fig. 13. (A) Relationship between average annual ground cover (%) and average annual suspended sediment concentration for the three hillslope flumes. The dashed line represents the median TSS concentration (122 mg/l) from the non-grazed plots at Meadowvale and (B) relationship between the average annual TSS concentration from Flumes 1 and 3 and the proportion of low cover D condition land on the hillslope. Note that the relationship derived in this figure is applicable for this catchment only and should not be extrapolated beyond the conditions under which it was developed.

representative of the top of the Flume 3 hillslope, then comparison of the differences in annual runoff between the flumes indicates between 51% and 86% of the Flume 3 runoff is generated from the bare scald area at the base of the slope. This analysis is supported by a previous finding that infiltration-excess runoff is generated first in areas with lower soil hydraulic conductivity (or infiltration) and then, depending on rainfall intensity, by hydrologically connected areas (Sumit et al., 2010). The spatial variability in runoff generation can also help to explain why the event runoff coefficients were weakly related to event maximum rainfall intensity for the Flume 1 hillslope (Fig. 10A), while McIvor et al. (1995) and Scanlan et al. (1996) instead found that rainfall intensity was a strong determinant of runoff coefficient.

A number of studies have shown that cover is a strong driver of hillslope runoff in semi-arid woodland environments (e.g. Boix-Fayos et al., 2006; Girmay et al., 2009; Scanlan et al., 1996), and cover is increasingly used to drive simulation models for such areas (e.g. Owen et al., 2003). Due to the large size of the hillslopes in this study, it is difficult to determine the precise mechanism through which vegetation is influencing runoff. Using small (1 m^2) rainfall simulators in this region, Roth (2004) found that runoff generation for high intensity events (~60 mm/h) was not influenced by vegetation until the proportion of ground cover was >75%. Pasture biomass has been found to affect runoff, and by inference soil infiltration in this study, but the effect is evident only during rainfall events below ~300 mm at the start of each wet season (Figs. 10C and 11A). Given that cover is still <75% on many parts of these hillslopes, it is likely that infiltration-excess runoff is still occurring at the point of rain impact, at least for early wet season events. As the ground cover increases in space and time, the vegetation appears to be capturing run-on from upslope and reducing the velocity sufficiently for water to start infiltrating into the soil. However, it appears that this process is only occurring for low rainfall amounts and intensities and/or for areas with very high cover (>75%).

The lack of response in annual runoff coefficient to improved GLM indicates that no significant change in soil infiltration rate occurred over the study period. Analysis of the amount of event rainfall above intensity threshold values did not reveal an increase in rainfall intensity over the study period that could have masked the detection of changes in soil infiltration rate. There are several reasons why vegetation cover did not affect annual runoff coefficients in this study. Firstly, it is likely that the relatively high stocking rates over the last few decades, combined with the associated compaction, and in many areas removal of the A-horizon, has increased the soil bulk density, reducing the hydraulic conductivity and infiltration capacity of the soil. The differences in bulk density values between high and low grazing intensity soils found in this study are similar to results from other studies (e.g. Sartz and Tolsted, 1974). The second possible reason is related to soil ecology (e.g. earth worm and termite activity). Holt et al. (1996) showed that both infiltration rates and Acari and termite populations were lower in heavily grazed sites compared with lightly grazed areas. Similar findings for earthworms are described in the review by Drewry (2006). In this study, soil bulk density and infiltration rates were highest adjacent to shrubs such as current bush (*C. ovata*) and Sandalwood (*E. mitchellii*), and stock do not regularly eat or trample on this vegetation (Roth, 2004). Thirdly, detecting a response in runoff coefficient was compromised by inter-annual variation in rainfall, with higher rainfall in latter years of the study. Whatever the contributing factors, it is apparent that there is a lag in the functional recovery of the soil condition at this study site. Wilcox et al. (2003) suggest that a slope threshold exists below which runoff and erosion will eventually return to pre-disturbance levels and above which runoff and erosion will remain at accelerated levels. This slope threshold is possibly a surrogate for the point at which vegetation becomes an important driver of runoff.

A number of other studies in the Burdekin region have shown that although sediment yields can differ greatly between different grazing treatments, mean annual runoff does not (e.g. Hawdon et al., 2008; McIvor et al., 1995; Scanlan et al., 1996). The maximum length of any of these studies was 6 years, and it is likely that soil hydrological recovery will take more than one decade, and possibly several before the infiltration capacity of the soil returns to 'natural' levels (e.g. Branson et al., 1981; Drewry, 2006). The recovery rate will also depend on the level of future grazing pressure. Good rainfall and low stocking densities may see further recovery and improvements within 10 years. If drought conditions return and/or stocking densities are increased, the recovery may take a lot longer (e.g. 20 years) or even be jeopardised all together.

This study found that the responses of hillslope runoff to improved GLM were smaller than those of hillslope sediment yield and runoff TSS concentration. The large reductions in sediment concentration (Fig. 13A) are consistent with a previous finding of an exponential decline in soil erosion rates with increasing vegetation cover (Gyssels et al., 2005). McIvor et al. (1995) suggested that these landscapes needed at least 40% cover to reduce runoff and sediment delivery from hillslopes. Roth (2004) increased this cover threshold to 75%. This study has shown that sediment yields start to decline when cover levels are the order of 50–75%. However, even 75% average cover was not sufficient for reducing annual runoff. The exponential relationship between the % ground cover and biomass for this catchment suggests that continued ground cover improvements will yield proportionally more biomass (Fig. 14). This relationship is relevant for sites with similar grass species, and may not be applicable to areas with different species composition. Obtaining cover levels of >75% may be challenging from a grazing enterprise point of view. These cover levels may, however, be what is required to facilitate hydrological recovery in this landscape; turning it into a 'conserving' rather than 'nonconserving' ecosystem (Ludwig et al., 2000; Wilcox et al., 2003).

Improving cover on the scald areas at the base of hillslopes and adjacent to the main stream channel would have a much larger influence on runoff and sediment yield at landscape scales than cover increases elsewhere. Other studies have also shown that best management practice has the greatest chance of improving downstream water quality when it is located in areas that are prone to generating runoff (Easton et al., 2008; Rao et al., 2009). Average cover levels of 60–70% may provide low sediment yields, provided the cover is evenly distributed and there are no low cover areas at the base of hillslopes. For managing catchment sediment yields, it may be more appropriate to set ground cover and biomass targets for two distinct zones: (1) lower slope areas that are generally

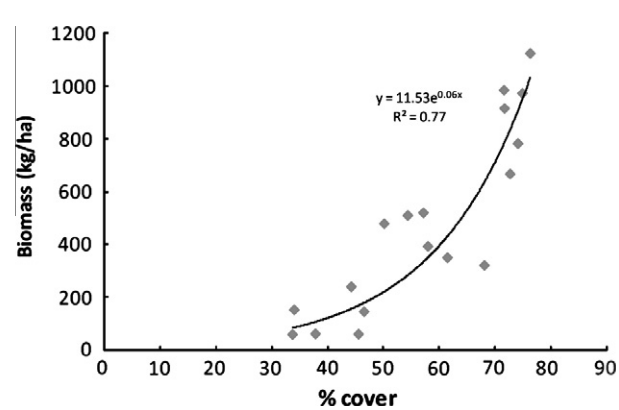

Fig. 14. Relationship between % cover and pasture biomass for all three hillslopes over the 6 year monitoring period.

highly utilised by cattle and (2) upper slope areas. Trialling a range of alternative strategies (e.g. fencing) for protecting low ground cover areas (and scalds) will likely be an important component of future GLM recommendations.

6. Conclusions

This paper presents the results of a 6 year field study of the impact of improved grazing management on vegetation cover and biomass, and the consequent loss of water and sediments from hillslopes in a tropical rangeland. It is concluded that pasture biomass and ground cover increased following the implementation of reduced pasture utilisation and pasture resting. It is also concluded that these improvements to GLM resulted in reduced hillslope runoff for the first runoff events of the wet season, however, the proportion of rainfall that turned into runoff did not decline at the annual scale. It is thus concluded that, in the short term at least, runoff is less sensitive to land use change compared to sediment yield. Hillslope sediment yields declined, apart from where areas with <10% vegetation cover were hydrologically connected to gullies and streams. Despite the improvements, further increases in ground cover and biomass, particularly on the low (<10%) cover sites at the bottom of hillslopes, are considered important for reducing runoff and sediment yield in the long term. For areas with <10% ground cover, more intensive rehabilitation is likely to be needed, particularly on the footslopes close to gully and stream networks.

Acknowledgements

The research presented in this publication was funded by Meat and Livestock Australia, CSIRO and eWater CRC; their support is gratefully acknowledged. The first author also received a CSIRO Payne-Scott award which contributed to this publication. We also thank Rob and Sue Bennetto on 'Virginia Park' Station and the Ramsay Family on 'Meadowvale' Station for access to their properties over 9 years to carry out this work. Thanks to Peter Fitch, Rex Keen, David Fanning, Jamie Vleeshouwer, Joseph Kemei, Lindsay Whiteman of CSIRO and the late Peter Allen for the installation of field equipment and collection of samples. Drs. Christian Roth, John McIvor, Peter Hairsine and Iain Gordon of CSIRO, and two anonymous reviewers, provided comments on early versions of this manuscript.

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