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Prepared by: Rebecca Bartley, Jeff Corfield, Aaron Hawdon, Brett Abbott, Rex Keen, Scott Wilkinson, Anne Kinsey-Henderson, Mike Nicholas

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Meat & Livestock Australia Limited
Locked Bag 991
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Recovery of the water cycle on grazing lands – cumulative impacts of changing pasture condition on retention of water, sediment and nutrients on Burdekin hillslopes

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Abstract

Meat and Livestock Australia (MLA) are committed to helping the Beef industry improve the quality and amount of water leaving grazed rangelands and reaching the Great Barrier Reef. This report summarises the findings of a 10 year study at Virginia Park Station in the Burdekin catchment that investigated the role of improved grazing land management (GLM) on hillslope and catchment water quality. The two management practices implemented in this study were: (1) reduced stocking; and (2) rotational wet season spelling. Ground cover and pasture condition were evaluated using on-ground surveys and remote sensing imagery. Subsequent changes to runoff and sediment yield were measured on hillslopes (using flumes) and at the end of the catchment (using automatic water sampling). During this study, average ground cover on hillslopes increased from ~35% to ~80%, although biomass levels are still relatively low for this landscape type, with ~16% of the cover increase attributed (in part) to improved GLM. The increased cover 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. There was a 40 to 90% reduction in hillslope sediment concentrations with the improved cover, although the high runoff meant that total sediment yield did not decline. Similarly, there has not been a reduction in runoff or sediment yield at the catchment outlet (14 km^2), as erosion from gullies and streamlines dominate sediment yields in this catchment. This study has shown that GLM in rangelands will potentially reduce impacts on downstream ecosystems, however, because of the multiple erosion sources, it will take more than 10 years for these changes to be detected at the end of the catchment.

Executive Summary

Degradation of grazing land resulting from unsustainable grazing practices can increase water, sediment and nutrient yields to downstream ecosystems. This report presents the results of a 10-year field study (2002-2011) that evaluated the impact of improved grazing land management (GLM) on ground cover, runoff and erosion at hillslope and catchment scales. The study was located in the Weany Creek catchment within the Burdekin River basin, on eucalypt woodland with a ‘native’ pasture understorey dominated by the invasive exotic grass, *Bothriochloa pertusa*. The two management practices implemented to improve pasture condition were reduced stocking (i.e., reduced pasture utilisation) and rotational wet season spelling.

Vegetation cover was measured using botanical field surveys and remote sensing techniques. Rainfall, runoff and sediment concentration were measured using flumes on three hillslopes ranging in size from 0.2 -1.1 ha, and using a stream gauge at the end of the 14 km^2 catchment. The annual average rainfall for the 10 year period (670 mm) was slightly more than the long term average rainfall (of 606 mm) for the area. Over the 10 year study period the ground cover increased by ~46% across the whole catchment. Following a comparison of cover data with a similar sized catchment that did not undergo changed GLM, ~16% of this cover increase can be attributed to GLM (and not increased rainfall).

At one of the flume sites, the amount of rainfall required to initiate runoff for the first event in each wet season increased significantly with the increase in ground cover. However, at the annual scale, the total amount of runoff increased during the study despite the increase in cover. This was because annual runoff is largely controlled by the storage capacity of the soil profile, and thus high rainfall years result in high runoff regardless of the amount of ground cover. Although there was no response to annual runoff with improved ground cover, there was a statistically significant reduction in total suspended sediment (TSS) concentrations on hillslopes that do not have large bare (<10% cover) areas connecting hillslopes to stream lines. TSS concentrations from 2 of the 3 flume hillslopes were not significantly different to data collected at sites exclosed from grazing once the ground cover reached ~70%. This suggests that if average ground cover can be maintained at, or close to, 70% over the long term, then hillslope TSS concentrations are likely to have a reduced impact on downstream ecosystems. The spatial arrangement, structure and composition of the ground cover is also important and areas with large bare patches (with <10% cover) can have erosion rates up to 70 times higher than areas without bare/scalded areas. The total erosion rates at sites with low cover patches (~0.25 mm/yr) are much greater than the soil production rates for rangeland environments and therefore this level of erosion potentially threatens the sustainability of these landscapes in the long term.

The end-of-catchment data followed a similar pattern to the hillslope flume results with runoff and sediment yields increasing during the study in response to increasing rainfall. The TSS concentrations had a weaker, but still significant decline in response to increasing ground cover in the catchment. The weaker link between cover and TSS concentration at this scale is expected as gully and bank erosion are known (from previous studies in the catchment) to contribute at least 60% of the end of catchment suspended sediment concentrations and loads, and channel erosion is not, at least in the short term, directly influenced by improved ground cover. Despite the dramatic improvements in ground cover in the catchment during the study period, the biomass levels are still lower than those recommended for this region, and this is due to the continued dominance by *Bothriochloa Pertusa* (Indian Couch). Further reductions in sediment concentrations at the end of the catchment may be possible in this landscape if the proportion of native deep-rooted perennial grasses can be increased. The results of this research are important for managing expectations with respect to water quality target setting, catchment water quality modelling and land management evaluation in the Great Barrier Reef catchments and in other extensive grazing environments.

Acknowledgments

The research presented in this publication was funded by Meat and Livestock Australia, CSIRO, Queensland Department of Primary Industries (now QDAFF), and eWater CRC. Their support is gratefully acknowledged. We also thank Rob and Sue Bennetto on ‘Virginia Park’ Station and the Ramsay Family on ‘Meadowvale’ Station for access to their properties over 10 years to carry out this work. Thanks to Brigid Nelson for her early contributions to the grazing management trial and to Peter Fitch, 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. Thanks also to Christian Roth, David Post and David McJannet to contributions towards the project management and analysis of data over the last decade.

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1 Introduction

Livestock grazing is Australia’s largest land use occupying 58% of the continent (www.brs.gov.au/landuse). Grazing is the dominant land use in the semi-arid and tropical rangelands of Northern Australia which are the watersheds for a number of ecologically sensitive receiving waters such as the Great Barrier Reef (GBR) World Heritage Area and the Gulf of Carpentaria in Queensland. In the GBR catchments there is concern that sediments and nutrients being exported from the land are at least five times greater than under pre-European conditions (McCulloch et al., 2003) and that they are having a detrimental effect on coral reef communities (Fabricius, 2005). In response to this issue, the Australian Government allocated $200 million in 2008, via the Reef Rescue package, to help land owners and managers implement improved land management practices (Brodie and Waterhouse, 2012). This investment is based on the assumption that paddock and end of catchment pollutant loads are sensitive to improved land management practices. There is, however, very little quantitative evidence anywhere in the world demonstrating that catchment-wide soil and water conservation programmes effectively reduce sediment fluxes from larger drainage basins (Walling, 2006). Where there is evidence for reduced end of sub-catchment sediment yields, the financial investments required for catchment restoration have been substantial. For example, Garbrecht and Starks (2009) and Kuhnle et al., (2008) showed a reduction in sediment yields over long (~60 year) time periods as a result of the combined effects of conservation tillage, terracing of cropland, gully shaping, grade control structures, channel stabilization, sediment trapping by water impoundments, and road surfacing in catchments ranging between 21 km^2 a 787 km^2. The actual cost of such activities were not documented in the publications, however, it is appropriate to conclude that such interventions are not likely to be cost-effective for grazing catchments the size of those draining to the Great Barrier Reef (~335,000 km^2).

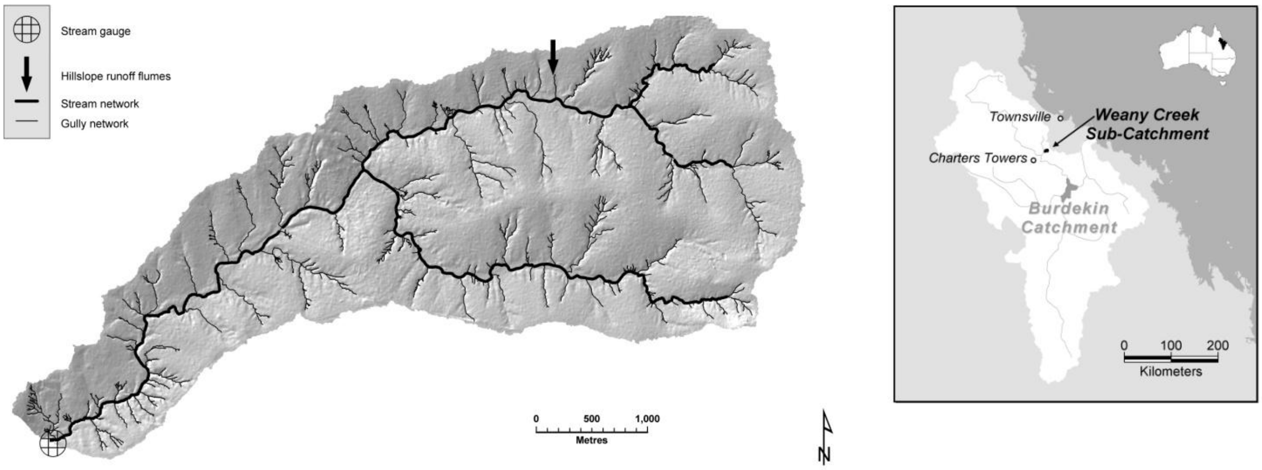
The primary factor that graziers can control, without major infrastructure investments, is ground cover or pasture biomass. Improvements in ground cover in grazing lands have been promoted as a mechanism for improving rangeland condition (Ash et al., 2011), improving property scale economic returns (MacLeod et al., 2009) and surviving in a variable climate (O'Reagain et al., 2011). A number of studies from rangeland areas suggest that vegetation clearing can increase runoff (Peña-Arancibia et al., 2012; Siriwardena et al., 2006; Thornton et al., 2007), however, few studies have evaluated the effectiveness of replacing or enhancing the amount of vegetation cover on catchment runoff (Wilcox et al., 2008), and even fewer studies have quantified the affect on catchment sediment yields. It is acknowledged that there is a non-linear relationship between sediment loss and increasing scale, from plot to hillslope to catchment (Ludwig et al., 2007) and that sediment yields in many rangeland environments are dominated by channel erosion sources (Tims et al., 2010; Wilkinson et al., 2012). There is significant Government investment aimed at improving water quality runoff from rangelands by increasing ground cover, therefore it is critical to understand the effectiveness of such actions on hillslope runoff and sediment yields at the property level over long (decadal) time-frames.

This report presents the results of a 10-year field study carried out in the Weany Creek catchment on Virginia Park Station in the Burdekin basin, Australia. A grazing management strategy that involved matching cattle numbers to pasture availability (thereby achieving sustainable levels of utilisation) and wet season resting, was implemented in the catchment in 2002. Pasture cover and biomass were measured at hillslope and catchment scales at the beginning of each wet season, and hillslope and catchment runoff and sediment yields were measured following runoff events between 2002 and 2011. The study site was set up in the Burdekin catchment as this catchment is the largest contributor of anthropogenic derived fine sediment to the GBR lagoon (Kroon et al., 2012), and the mouth of the river is located near a number of economically and globally significant marine areas (Brodie et al., 2009). Importantly, these data were collected from this field site while it was operating as a commercial grazing property. The initial 6 years of monitoring results (2002-2007) were presented in Bartley et al. (2010a) for the hillslope data, and in Bartley et al. (2010b) for the catchment-scale runoff and sediment yield responses. There have been several very wet (above-average rainfall) years in the final 4 years of the study (2008-2011) which has shed new light on the role of pasture in controlling runoff and erosion in these grazed rangelands. This report will present the total decade of monitoring results for this site, and discuss the implications of these findings for grazing land management and off-site water quality.

2 Field Site

The Weany Creek catchment (S19°53’06.79’’, E146°32’06.65’’) resides within a commercial cattle grazing station (Virginia Park) which is covered by Eucalypt savannah woodland in the Burdekin catchment of northern Australia (Figure 1). A map of the Virginia Park property and the location of the four study paddocks are shown in Figure 2. The property is located in a headwater catchment with an area of ~14km^2 and long term (1900-2011) average annual rainfall of ~ 604 mm (St. Dev. = 253 mm). This site was chosen due to its location in an area identified as having high rates of soil erosion, with between 52% (Kinsey-Henderson et al., 2005) to 67% of river sediment estimated (using modelling) to be coming from hillslope sources (Prosser et al., 2001). The property had also been grazed for over 100 years, and the landholders were willing to trial more sustainable grazing techniques.

A detailed description of the soils and vegetation in the Weany Creek catchment can be found in previous publications (e.g. Bartley et al., 2010a). In brief, the soils are generally infertile Red Chromosols and Yellow to Brown texture contrast soils. Numerous scalds with low ground cover are found along riparian areas on unstable duplex soils. The vegetation is a mixture of ironbark/bloodwood communities (e.g. narrow-leafed ironbark, *Eucalyptus crebra* and red bloodwood, *Corymbia erythrophloia*) and shrubby species (e.g. currant bush, *Carissa ovata* and false sandalwood, *Eremophila mitchellii)*. Pastures are dominated by the exotic, but naturalised stoloniferous grass Indian Couch (*Bothriochloa pertusa*) mixed with native tussock grasses (e.g. *Bothriochloa ewartiana, Heteropogon contortus* and *Chrysopogon fallax)*.



(A)

(B)

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

3 Methods

3.1 Grazing management strategy

The two management practices implemented in this study were: (1) reduced stocking/utilisation; and (2) rotational wet season resting (WSR) in alternate years. A full description of the grazing management carried out in each paddock is given in Bartley et al., (2010a and b). Utilisation rates were applied based on standing dry matter using the methods described in Post et al., (2006). The annual stocking rates averaged for the 3 study paddocks and proportioned by stocking days are presented (in hectares per animal equivalent, Ha/AE) (Table 1).

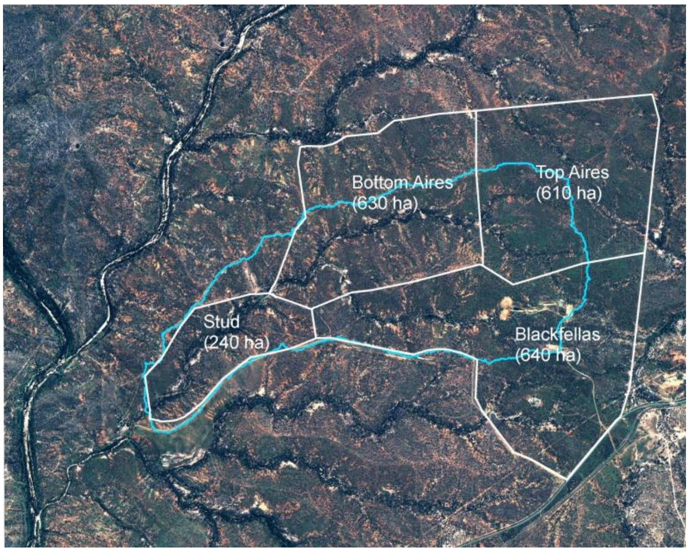


Figure 2: Study location showing the Weany Creek catchment boundary (blue line) and the paddock boundaries on Virginia Park Station (white lines). The background is a pan-sharpened real-colour image derived from the Quickbird^{TM} satellite, taken in December 2003.

Table 1: Annual rainfall (measured at Flume 1), timing of wet season rest (WSR) in each paddock and annual stocking rates averaged for the 3 study paddocks (hectares per animal equivalent, ha/AE) for 2002-2011.

Paddock	Prior to trial	2002-03	2003-04	2004-05	2005-06	2006-07	2007-08	2008-09	2009-10	2010-11	2011-12
Rainfall (mm)		304	245	382	431	706	760	1308	630	1172	746
Top Aires		WSR		WSR		Late WSR			Early WSR		Late WSR
Bottom Aires (flume paddock)			WSR	WSR		Late WSR	Early WSR		WSR	Early WSR	WSR
Blackfellas			WSR		WSR		Late WSR		Late WSR		Early WSR
Average paddock Stocking rate (ha/AE)	4	29.9	21.6	14.6	11.4	6.4	7.1	7.1	7.5	4.9	12.8

3.2 Hillslope scale data

3.2.1 Site selection

To estimate the impact of improved pasture management on land condition and subsequent water and sediment loss at the hillslope scale, three hydrological flume hillslope sites were established in 2002. These flumes were located within 400 metres of each other in the Bottom Aires paddock (Figure 1). As rangeland systems have characteristically patchy cover patterns (Ludwig et al., 2005), the three flume sites were chosen to represent different vegetation arrangements. Approximately 7.5% of the hillslope above Flume 1 had <10% cover, however, these bare areas were located on the side of the flume hillslope and were not in the main flow path (Figure 3A). Flume 2 had an even cover pattern with no major bare areas. Flume 3 had ~7.7% of its surface represented by areas with <10% ground cover in 2003, however, the low cover was all located at the bottom of the hillslope directly in the main flow path (Figure 3C). The hillslopes are described in more detail in Bartley et al., (2010a; 2006). Characteristics of each flume site, as well as the 10-year average rainfall data are given in Table 2. The 10-year average rainfall at the flumes sites was similar to the long term average of 604 mm recorded at Fanning River Station (1900-2011 patched SILO data), however, the first half of the study generally had below average rainfall, and the second half of the study was much wetter. No research funding was available for the 2008 wet season and therefore only minimal data for this year are available.

Table 2: Description of the area, slope %, slope length and distance from the stream of the three hillslope flume sites. The 10 year average rainfall for each site is also presented.

Paddock	Flume 1	Flume 2	Flume 3
Area (m^2)	11 930	2031	2861
Mean Slope (%)	3.9	3.1	3.6
Slope length (m)	240	130	150
Distance from gully or stream network (m)	~50 m	~250 m	<20 m
Proportion of hillslope with <10% cover at beginning of study	~7.5%	<1%	~7.7%
Average Rainfall at site over 10 year period (mm)	~695	~666	~672

3.2.2 Ground cover and biomass

Hillslope ground condition was measured at each flume site using end of dry season surveys across each hillslope on an 8 × 4m grid. For each grid point, pasture condition metrics were recorded using a 1 m quadrate. Data measured included 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 (see Tongway and Hindley, 1995). The on-ground cover measurements were summarised as total projected ground cover (TPGC) and represented the % of cover that would be seen from above (whether at ground level or from remote sensing). There the total % cover at each site includes standing dry matter plus litter. The proportion of decreaser, native, perennial grasses (DNPG) were also recorded at each flume site except in the very low cover years (2003 and 2004) when these measurements were too difficult to measure (due to extremely low biomass). DNPG grasses are those that decrease when animal numbers exceed carrying capacity for a sustained period of time (Ash et al., 2011). Vegetation/land type, landscape location and tree canopy cover was also recorded within a 10 m radius from each grid point. In addition to on-ground field measurements of cover, Quickbird satellite images with a resolution of 2.4 m^2, were analysed to estimate the areas of each hillslope flume site with <10% ground cover. This was done for seven out of ten years of the study, as for three of the years (2002, 2008 and 2011) there were either no cloud free days or funding issues limiting data collection.

3.2.3 Hillslope scale runoff and erosion

To measure water and sediment runoff, a large Parshall flume was used for Flume 1, and 9 inch cut-throat flumes were used for Flumes 2 and 3. Details describing the flume instrumentation can be found in Bartley et al., (2006). Total suspended sediment (TSS) samples were collected using depth stratified sampling at Flume 1, and bulk drum sampling for Flumes 2 and 3. TSS concentrations were considered to represent the silt (0.002–0.063 mm) and clay (<0.002 mm) fractions. Bedload samples (representing sediment between 0.063 and 8mm) were collected downslope from each flume. Sediment loads were calculated by summing the event loads using the arithmetic mean approach (Letcher et al., 1999). At flume 1, the median TSS values for the whole season were used when no samples were collected. In previous publications (Bartley et al., 2010a; Bartley et al., 2006), the average TSS value was applied, however, with 10 years of data it was possible to identify some of these values as outliers, and therefore the median was more appropriate. At Flume 2 and 3, the median concentration of the sample collected in the drum was applied to all previous events leading up to the collection date. At Flume 3, there were 3 years with very high TSS values that were well above the 90th percentile confidence limits for the 10 year data set (see Figure 6A). These values generally occurred at the beginning of large runoff events when the bulk sampler filled up rapidly only collecting the high concentration first flush sediment (described in Bartley et al., 2006). These outlier values were replaced with an average concentration TSS value from that event as well as the events pre and post that occurrence. This reduced the bias in the final load estimates. There was sensor malfunction at Flume 2 in 2002/03 and 2008/09 and at Flume 3 in 2009/10 and no data were presented for these years.

The flume data collected over the 10-year study were compared with TSS samples collected from similar hillslope runoff troughs from an exclosure site at the nearby Meadowvale cattle station. This site has similar geology and soil type and has had light or no cattle grazing for ~20 years. Further details of the Meadowvale site data is available in Bartley et al., (2010a) and Hawdon et al., (2008).

There was some vegetation recovery on the scald site on Flume 3 in the early years of the study, however, this recovery had been very slow compared with the scald sites on Flume 1 (Bartley et al., 2010a). In an attempt to fast track the vegetation and scald recovery on Flume 3, and reduce sediment loss from this site, a sheet metal bunding wall was installed around the scald area on Flume 3 in January 2012. This was part of a project looking at various restoration options for facilitating the recovery of these scald features in rangeland grazing systems. The bunding was ~300 mm high and covered an area of ~550 m^2, which is ~20% of the Flume 3 runoff area. It is anticipated that the bunding will divert upslope runoff away from the scald area and speed up the colonisation of pasture to stabilise this site.

3.3 Catchment scale data

3.3.1 Catchment Ground cover

It was not practical to physically measure ground cover for the entire catchment (~1400 ha), therefore Quickbird satellite images (with a 2.4 m^2 resolution) were used to estimate catchment cover. To evaluate the effect of the grazing management trial against the background rainfall variability, Quickbird imagery was also collected and analysed for an un-named property adjacent to the Weany Creek catchment that has similar biophysical characteristics. The 'control' property is a similar size to Weany Creek (~1250 ha) but, to our knowledge, it did not undergo changed grazing management between 2002 and 2011. Both properties were analysed for average ground cover in 2003, 2005, 2006 and 2007, 2009 and 2010. As with the flume sites, the entire Weany Creek catchment was also analysed for areas with <10% ground cover.

3.3.2 Catchment Runoff and sediment yields

An automatic gauging station that measured catchment runoff and sediment concentration was installed at the outlet of Weany Creek in 1999. This instrumentation was used to monitor the change in runoff and sediment flux for 2 years prior to the grazing management trial (2000-2001) and for 10 years during the trial. The gauging station recorded rainfall, stage height, flow velocity, turbidity and water temperature at one-minute intervals during events, noting that Weany Creek is ephemeral during low rainfall years and flows for ~5% of the year. In above average rainfall years, the creek may flow for more than 6 months of the year. Details of the monitoring equipment and water sampling design of the gauging site are given in Bartley et al., (2007; 2010b). To estimate sediment concentration, a 1 L water sample was collected at programmed intervals across the hydrograph. A linear relationship between total suspended sediment (TSS) and turbidity was developed using data from 2000-2006, and applied to the 2000-2006 period. A new turbidity sensor was installed in 2007 and a revised relationship was applied from 2007-2012. These relationships were then used to calculate the annual suspended sediment load for each water year (July 1 to Jun 30). Bedload was not sampled at the catchment outlet. Event mean concentration (EMC) values for TSS concentration were calculated for each year using the method described in Bartley et al., (2010b). Average catchment rainfall, which is the average of rainfall recorded at the stream gauge and Flume 1, is reported with the catchment runoff results.

4 Results

4.1 Hillslope scale

4.1.1 Cover, biomass and pasture condition

Table 3, Table 4 and Table 5 present the end of dry season ground cover and biomass levels and the area of low (<10%) cover for Flumes 1, 2 and 3, respectively. Cover represents the combination of standing dry matter and litter (both attached and un-attached vegetation). The lowest annual rainfall at the flume sites (<250 mm), and the lowest ground cover, occurred in the 2003 wet season (July 2003- June 2004). Ground cover in 2003 was between 34 and 45% at the 3 hillslope sites, and biomass was around 60 kg/ha. Following improved rainfall and a further 8 years of conservative stocking, cover in 2011 was ~80% on all hillslopes and biomass was >1100 kg/ha. The change in the amount and spatial distribution of cover between 2003 and 2010 for Flumes 1 and 3 are shown in Figure 3. The biomass levels peaked in 2009 with >2500 kg/ha across all flume sites, however, there was a large (district wide) collapse in Indian Couch biomass in 2010 (due to unknown causes) and this resulted in reduced biomass for that year. The area with <10% cover has declined on all three hillslopes (see Table 3, Table 4 and Table 5). The change in cover over the 10 year study was not evenly distributed across the hillslope and the upper slope ironbark and bloodwood dominated areas had more rapid cover recovery than the lower slope sandalwood sodic soil areas (Figure 4A). Importantly, the percentage of ground cover on the lower slope sodic areas of Flume 3 increased from ~20% in 2005 to 52% in 2011. There is also evidence of earth worm and termite activity at this site indicating improved macro-invertebrate activity in response to increased litter and dry season soil moisture. The proportion of decreaser, native, perennial grasses (DNPG) contributing to total biomass has also increased during the study, and the percentage of DNPG now represent ~15%, 20% and 25% of the total biomass at Flume 1, 2 and 3, respectively (Figure 4B). This is a considerable increase from the original representation of <7% across all flume sites in 2002. It is likely that the vegetation trends were strongly related to the sequence of 4 very dry years followed by 6 average to above average years.

Table 3: Cover attributes for Flume 1. Standard error (SE) in brackets. Cover measured at end of dry season. NA = no data collected

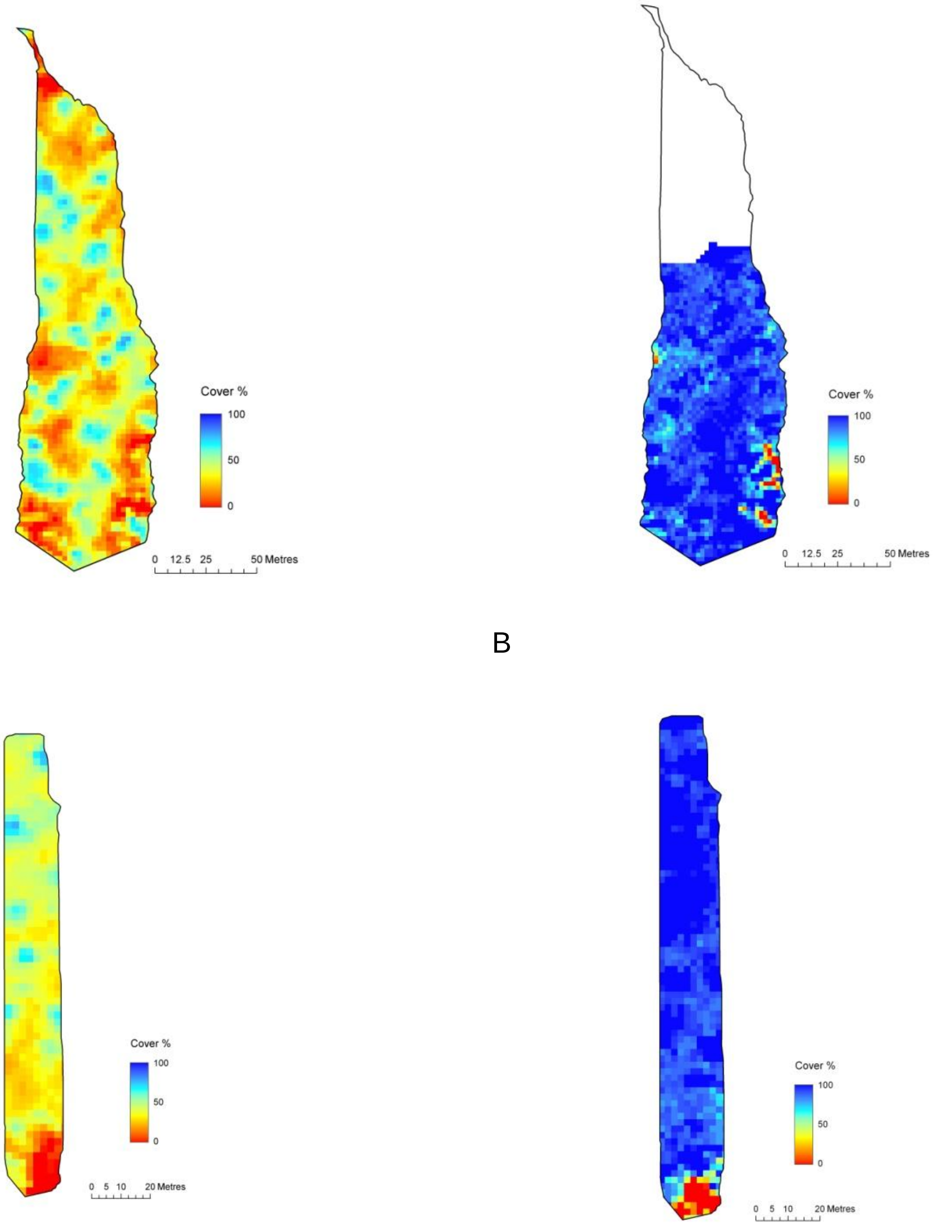
	Field data		Quickbird data
Year	Average cover (%) (SE)	Pasture biomass (kg dry matter/ha) (SE)	% of land with < 10% ground cover
2002	61.5 (0.8)	347 (6.9)	-
2003	33.8 (0.3)	59 (4.0)	7.5
2004	44.3 (1.1	240 (14.1)	3.2
2005	57.2 (1.1)	521 (17.9)	3.6
2006	71.7 (1.2)	915 (44.4)	1.2
2007	71.6 (1.2)	984 (39.0)	1.5
2008	NA	NA	Na
2009	84.5 (1.1)	2515 (71.38)	0.58
2010	88.7 (0.7)	521 (15.4)	0.76
2011	83.5 (0.7)	1186 (22.6)	NA

Table 4: Cover attributes for Flume 2. Standard Error (SE) in brackets. Cover measured at end of dry season. NA = no data collected

	Field data		Quickbird data
Year	Average cover (%) (SE)	Pasture biomass (kg dry matter/ha) (SE)	% of land with < 10% ground cover
2002	58.0 (0.9)	393 (13.9)	-
2003	37.9 (0.5)	62 (3.2)	<1%
2004	34.1 (1.8)	153 (12.3)	<1%
2005	50.2 (1.8)	479 (22.3)	<1%
2006	74.1 (2.4)	782 (39.5)	<1%
2007	76.3 (1.5)	1123 (75.3)	<1%
2008	NA	NA	Na
2009	85.6 (1.8)	3291 (131.5)	0%
2010	90.2 (0.8)	576 (32.4)	0%
2011	78.8 (1.5)	1083 (39.5)	NA

Table 5: Cover attributes for Flume 3. Standard Error (SE) in brackets. Cover measured at end of dry season. NA = no data collected

	Field data		Quickbird data
Year	Average cover (%) (SE)	Pasture biomass (kg dry matter/ha) (SE)	% of land with < 10% ground cover
2002	68.1 (1.3)	321 (7.5)	-
2003	45.6 (1.0)	61 (3.5)	7.7
2004	46.6 (1.4)	146 (10.5)	6.7
2005	54.4 (2.1)	510 (23.3)	6.7
2006	72.7 (2.7)	667 (38.5)	5.3
2007	74.9 (1.8)	972 (47.0)	7.0
2008	NA	NA	Na
2009	81.9 (1.7)	2517 (87.8)	3.32
2010	85.5 (1.4)	634 (29.7)	3.48
2011	81.4 (1.7)	1196 (40.8)	NA



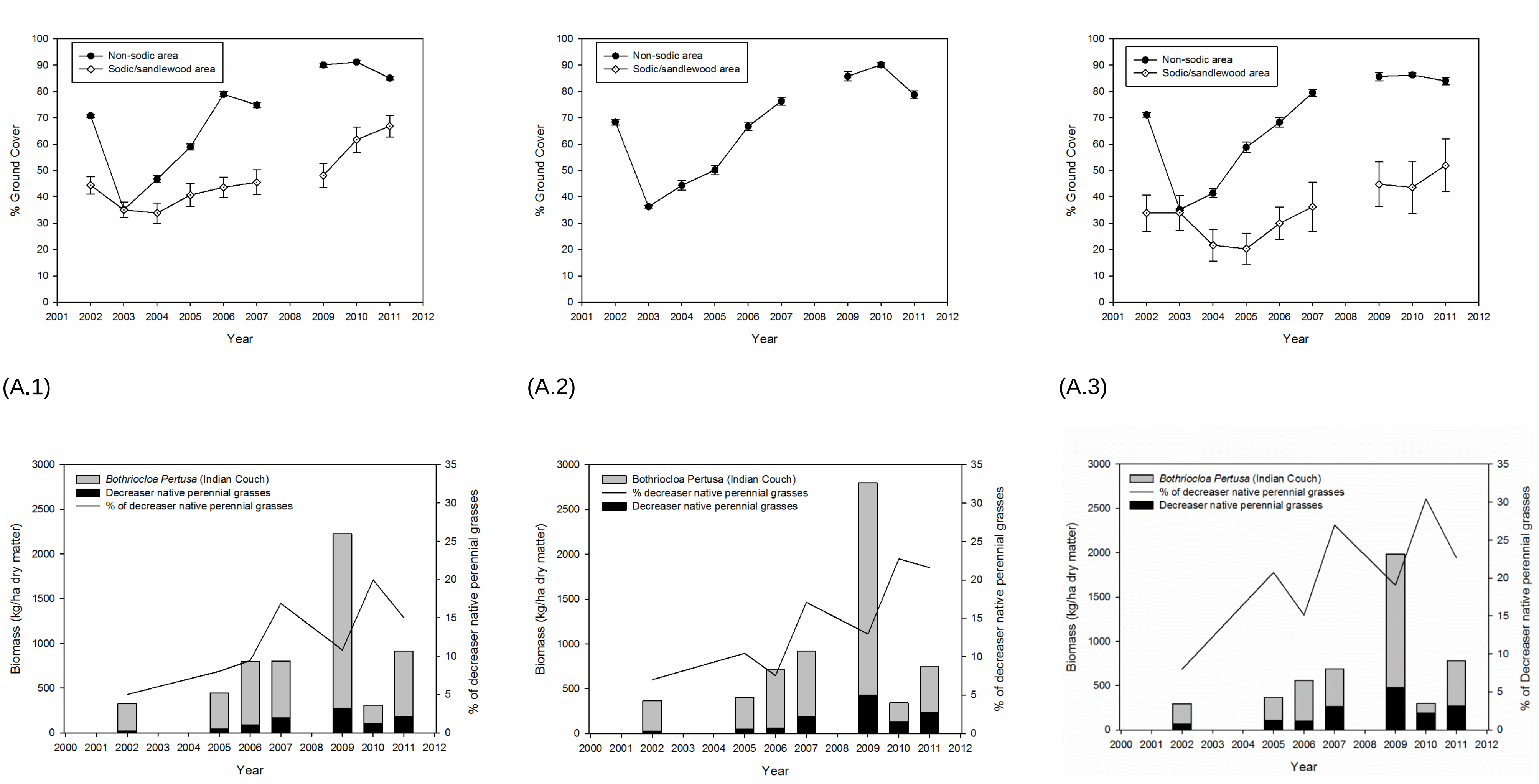
A

B

C

D

Figure 3: Comparison of the arrangement of ground cover on Flume 1 in 2003 (A) and in 2010 (B) and for Flume 3 in 2003 (C) and 2010 (D). Data based on Quickbird imagery. The top of flume 1 was obscured by cloud at the time of data capture.



(A.1) (A.2) (A.3)

(B.1) (B.2) (B.3)

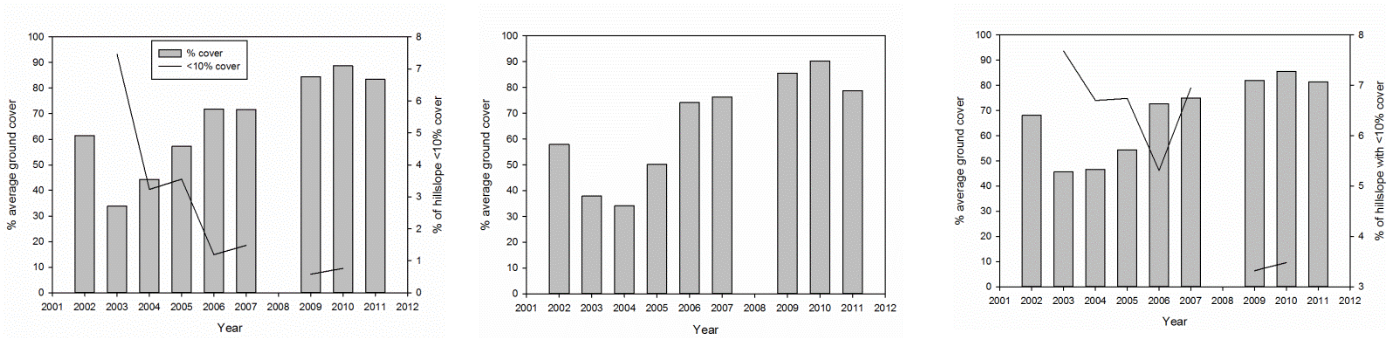
Figure 4: (A) the difference in % ground cover change on Flume 1 (A.1), Flume 2 (A.2) and Flume 3 (A.3) between the ironbark-bloodwood areas without sodic bare patches, and the lower slope sodic areas with typically <10% ground cover. Noting that Flume 2 did not have any sodic low cover areas; (B) the proportion of total biomass that is made up of *Bothriocloa Pertusa* (a stoloniferous grass) versus the decreaser native perennial grasses on Flume 1 (B.1), Flume 2 (B.2) and Flume 3 (B.3). Data measured at the end of the dry season.

4.1.2 Hillslope scale runoff and erosion

The average cover was very similar across each of the 3 hillslopes flume sites during the 10-year study period (Figure 5A) as was the distribution of rainfall (Figure 5B). The amount of runoff at each site generally follows the rainfall pattern, however, the proportion of rainfall that turned into runoff (or % runoff) over the study period varied considerable between the flumes (Figure 5B). The % runoff increased slightly at Flume 1 and 2 over the study period, generally increasing in years with higher rainfall, despite the increase in ground cover. This suggests that the soil profile, and its capacity to absorb rainfall, plays a strong role in determining the amount of runoff at each site. There is, however, a strong exponential relationship between the % average ground cover at Flume 1 and the amount of rainfall required to initiate runoff over the 10 year period (Figure 6A). This was calculated as the amount of rainfall that fell on the hillslope (since July 1 of the runoff year) before runoff was initiated at the Flume sensor. The same relationships did not, however, hold for Flumes 2 and 3. Rainfall intensity data for 2002-2007 (I15 and I30 values) were presented in Bartley et al., (2010a) and were not shown to significantly impact on the proportion of rainfall that turns into runoff for individual events on Flume 1. Therefore, this result demonstrates that although total annual runoff is likely to be controlled by the soil profile, the amount of vegetation does influence the amount of rainfall that is absorbed into the soil, particularly at the beginning of the wet season. Flume 3 had very high % runoff values (up to 58%) which increased up until 2008, after which the values fell to <15%. The reduction in % runoff in 2012 is likely due to the installation of the bunding wall around the scald area at the bottom of Flume 3, but it also reflects the change in ground cover in this area which is now ~52% for the lower scalded area and 84% for the Flume 3 hillslope site in total.

Although the average cover was similar between the flume sites, the amount, distribution and persistence of areas with <10% cover varied, and this had an influence on the amount of soil erosion. The TSS concentrations changed most dramatically on Flume 1, the largest of the 3 hillslopes (Figure 5C.1). When an ANOVA (on ranks) is used to compare the Flume 1 TSS data to data collected at the low impact neighbouring Meadowvale site, it is found that data from 2005 (and all previous years) is significantly higher (p= 0.819) than the Meadowvale data. The ground cover on Flume 1 in 2005 was 57%. There is no significant difference (p=0.005) in the TSS concentrations measured on Flume 1 in 2006 compared to the Meadowvale data. The average ground cover on Flume 1 in 2006 was 72%. This suggests that there is a threshold change in water quality concentration when cover increases above 70%. The TSS concentrations did increase slightly on Flume 1 in the later years of the study, however, this is considered to be related to the higher runoff in later years. There is a similar pattern in TSS concentration for Flume 2, where TSS values decline, and stay low, once ground cover is >70%. The TSS concentrations at Flume 3 do not show a systematic change over the 10 year period and in all years the values are significantly higher than the Meadowvale values (Figure 5C.3).

The sediment load data presented in Figure 5D are a multiplication of the TSS concentration and runoff data, and are generally biased by high rainfall and runoff years. As a result, the annual sediment loads did not decline over the 10 year period at any of the flume sites. Flume 1 experienced a decline in sediment load with increasing ground cover up until 2007 (Bartley et al., 2010a) after which time a number of above average rainfall years occurred which changed this pattern. Flume 3 showed a large reduction in sediment yield between 2008 and 2011, however, this is likely to be directly related to the bunding wall, and not grazing land management, as 90% of the runoff for the 2011/12 wet season occurred after the bunding was installed. The total sediment loads at Flume 3 remained, on average, 25 times higher than Flume 1, and ~70 times higher than Flume 2. Given that the runoff volumes were not that different between Flumes 1 and 3, most of this can be explained by the high TSS concentrations measured at Flume 3 (Figure 6B). The elevated TSS concentrations and high runoff ratios measured at Flume 3 have resulted in a total sediment loss of ~2.5 mm across the whole hillslope over the 10 year period (Figure 6C). This is much higher than the 10 year total soil loss rates measured at Flumes 1 and 2 of 0.11 mm and 0.03 mm, respectively.



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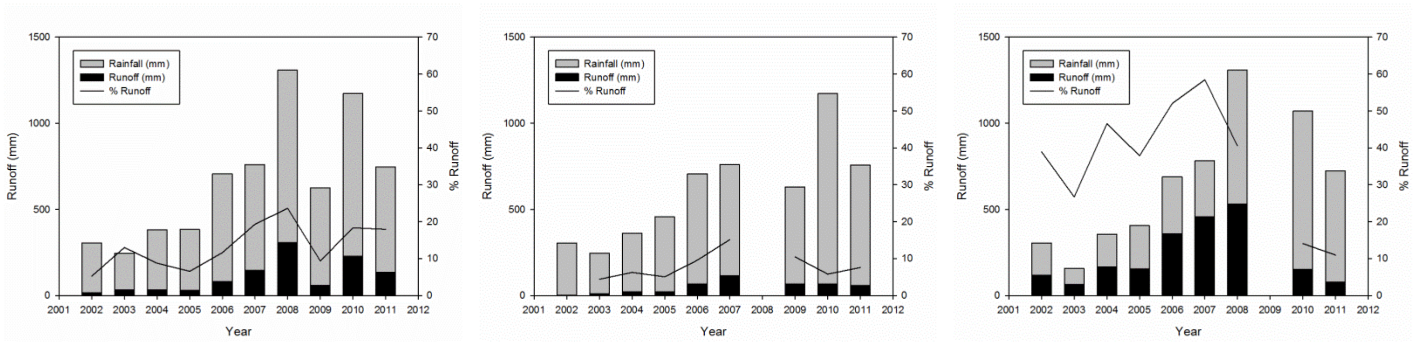

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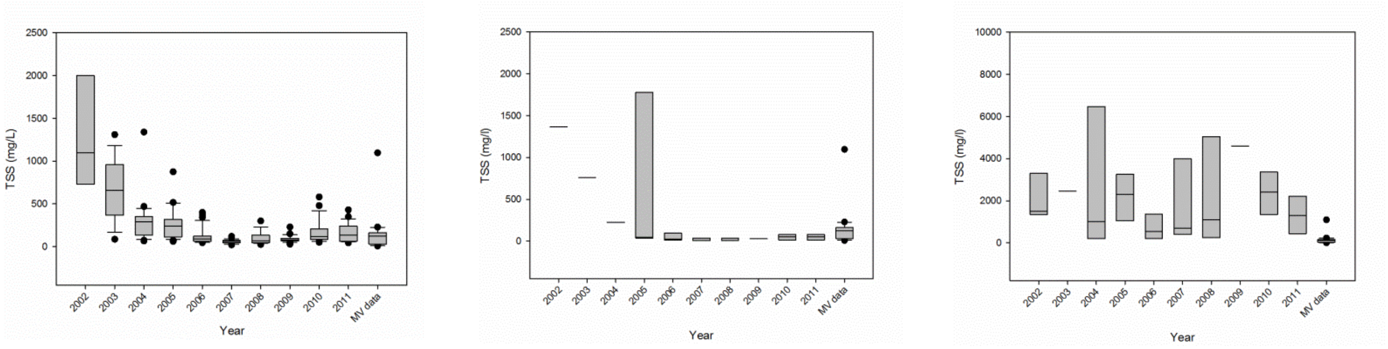

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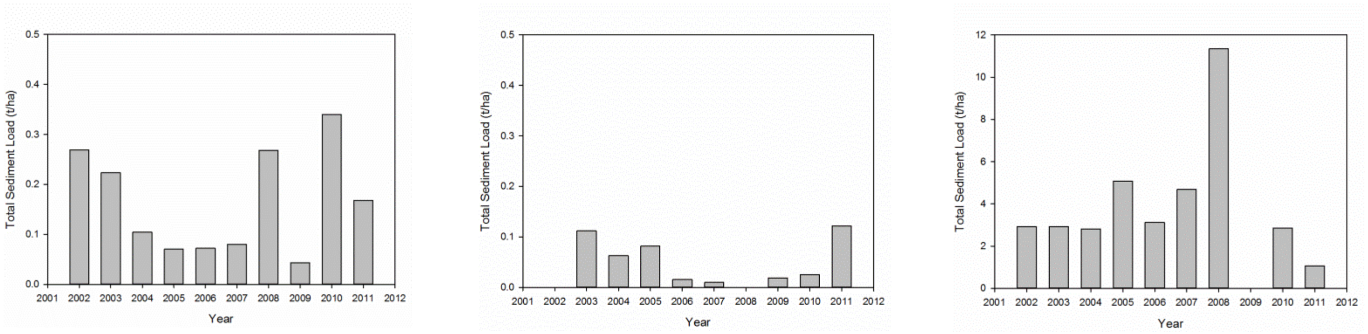
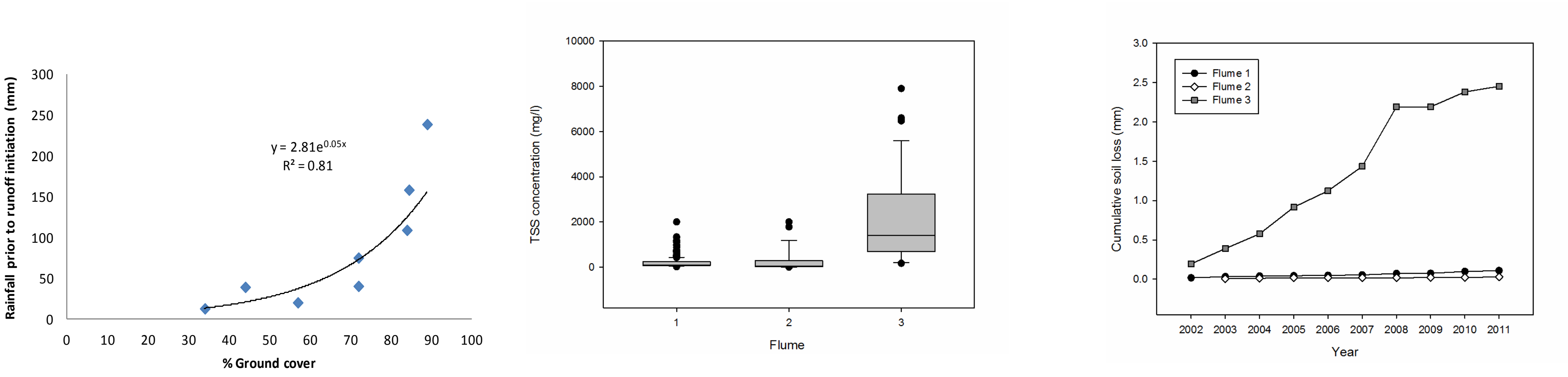


(D.1) (D.2) (D.3)

Figure 5: (A) Changes in % ground cover between 2002 and 2011 of each of the flume sites. No cover data was collected at any of the sites in 2008; (B) Changes in % runoff and runoff over the 10 year study period at each of the

flume sites; (C)Total suspended sediment (TSS) values for each flume site compared with the Meadowvale (MV) data from the grazing exclosures described in Hawdon et al., (2008). The same MV data was used in all 3 graphs, however, the scale of the y axis varies. The black dots represent outliers in the data set (> 95% confidence interval). The top and bottom horizontal lines on the box plots are the 75th and 25th percentile values, respectively; (D) Changes in the sediment yield (t/ha) over the 10 year study period at the three flume sites. No data were available in 2008 at Flume 1 and in 2009 at Flume 3 due to sensor malfunction. Note that all similar graphs have the same Y axis values, with exception of C3 and D3.



(B)

(C)

(A)

Figure 6: (A) The amount of rainfall prior to runoff initiation at Flume 1 (2003-2011); (B)Range of TSS samples collected at Flume 1, 2 and 3 over the 10 year study and (C) the cumulative soil loss in mm over the 10 year period

4.2 Catchment scale

4.2.1 Ground cover

Ground cover for the entire Weany Creek catchment followed a similar pattern to the flume hillslopes. The average catchment cover in 2002, at the beginning of the changed grazing regimes, was 45%. After 10 years the average ground cover was 92% across the catchment, an increase of 47%.The increase in cover was largely due to the increased rainfall over the 10 years of the study, however, improved grazing management strategies have also contributed to the improvements. The change in cover at an adjacent property that did not undergo changed grazing management was 31% over the same period, suggesting that there was a significant influence of improved grazing management (nominally 16% ground cover increase) (Figure 7). The evidence for this is change in cover is circumstantial (as no data were collected on the control property) but the result is consistent with expectations or with trends from a replicated grazing trial located in the south-west of the Upper Burdekin catchment (O'Reagain et al., 2011). The increase or change in ground cover was not evenly distributed across the catchment. The upslope areas re-covered first, followed by the mid-slope areas (Figure 9). The remaining low (<10%) cover areas are on the lower slopes and areas adjacent to the drainage lines (Figure 10). The low cover areas that remain in 2011 largely represent the severely scalded and gullied sites such as the lower section of Flume 3.

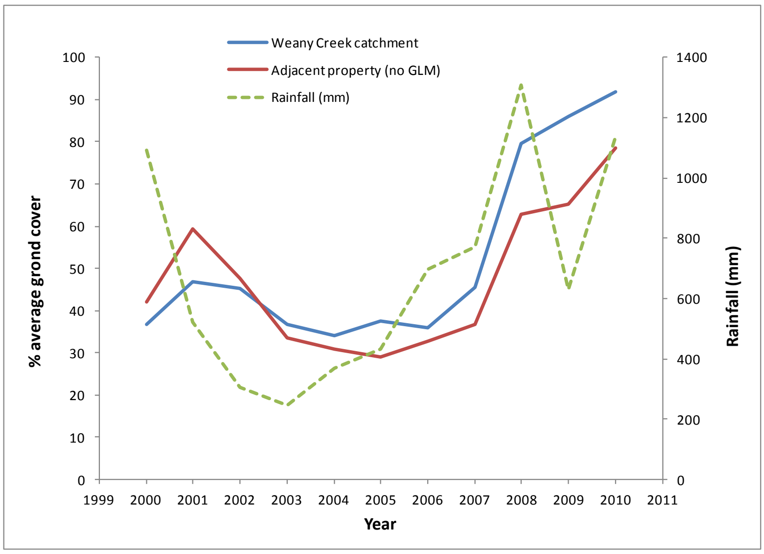


Figure 7: Annual average catchment ground cover (%) for the Weany Creek catchment and the adjacent property that did not have changed grazing management from 2002

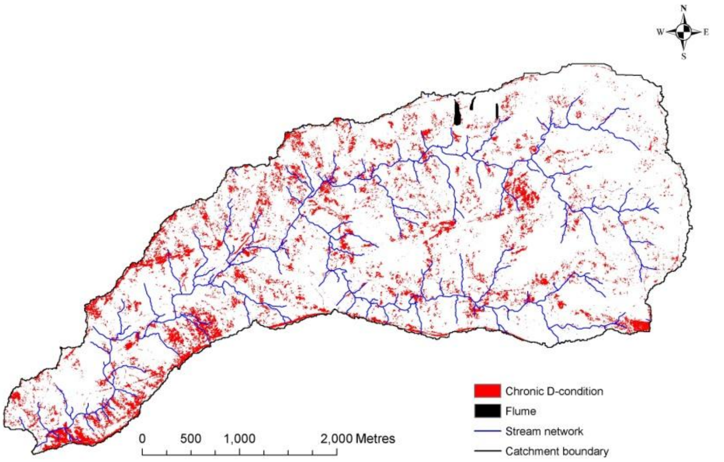


Figure 8: Proportion of catchment with <10% cover in November 2003

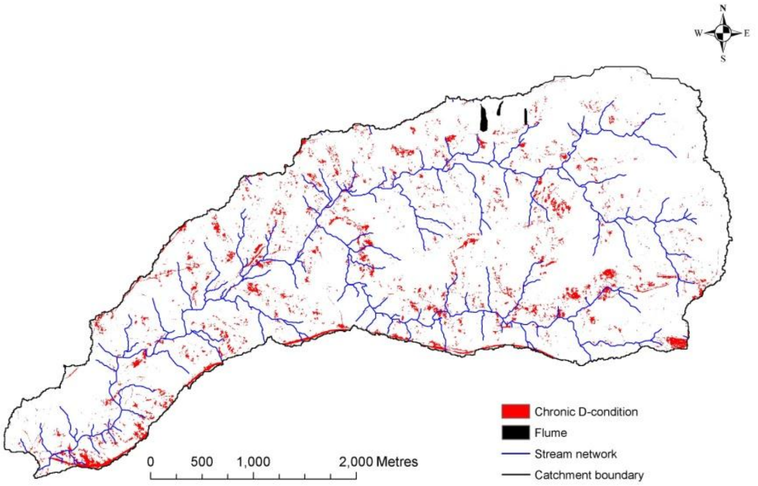


Figure 9: Proportion of catchment with <10% cover in November 2007

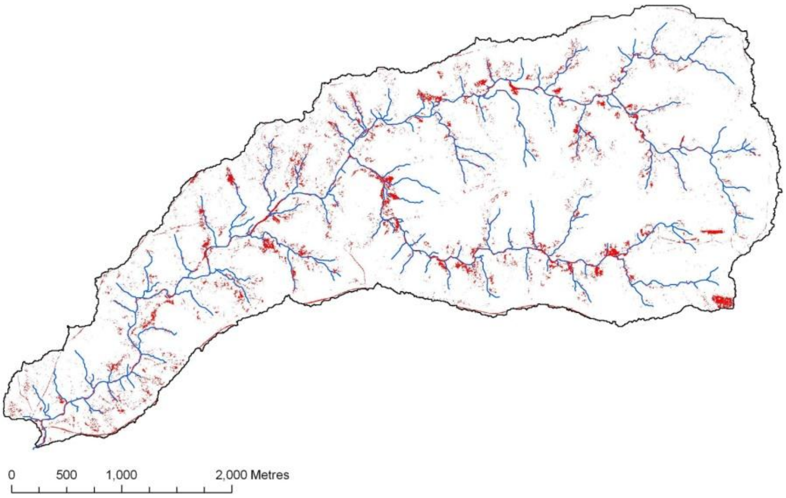


Figure 10: Proportion of catchment with <10% cover in November 2010

4.2.2 Catchment scale runoff and sediment yields

The grazing management trial was initiated in the Weany Creek catchment in 2002, corresponding to the beginning of a run of 4 years of below average rainfall (Figure 11A). The second year of the trial (2003) had only 37% ground cover and it had the lowest catchment runoff (Table 6), but the highest average annual TSS concentrations in the 10 year record (Figure 11B). The low runoff resulted in the lowest sediment loads during the study (Figure 11C). There was a steady increase in rainfall and runoff over the 10 years of the grazing management trial, with the highest % runoff and sediment loads occurring in 2008 (Figure 11A). The runoff and sediment loads increased during the study despite the % catchment ground cover increasing from 45% to 92% (Table 6). This result is similar to the flume data that suggests that although ground cover has some influence on the timing and volume of runoff experienced in early wet season events, once the soil profile has been saturated, the remaining rainfall will turn into runoff. Despite cover having little influence on catchment runoff, there was a decline in the TSS concentration during the study. There is a significant ($p = 0.038$) exponential relationship between average catchment cover and the event mean concentration (EMC) values for TSS measured at the stream gauge (Figure 11D). This suggests that the improvements in cover measured in the catchment have had an impact on the concentrations of sediment reaching the catchment outlet. The direct mechanism for this reduction in concentration is likely to be related to a combination of reduced hillslope erosion, but also the role that the increased vegetation has played in reducing soil detachment and possibly increased sediment trapping on scald and gully features within the catchment in areas where cover has increased.

Table 6: Catchment cover, rainfall, runoff and sediment concentrations and loads measured at the stream gauge between 2000 and 2011

Year (wet season begins)	Average catchment cover (%)	Average catchment Rainfall (mm)	Runoff (mm)	% Runoff	Fine sediment yield (t)	Event mean concentration (mg/L)	Number of TSS samples collected
*2000**	*37*	*581*	*18*	*3*	*388*	*1552*	*19*
*2001**	*48*	*582*	*28*	*5*	*972*	*2593*	*45*
2002	45	303	12	4	410	2425	20
2003	37	315	9	3	455	3762	10
2004	34	368	25	7	699	2076	12
2005	38	517	10	2	373	2828	19
2006**	36	756	112	15	2212	1458	29
2007	46	707	140	20	1603	843	37
2008	80	1224	418	34	4031	711	35
2009	86	600	104	17	1409	998	21
2010	92	1217	181	15	2128	865	55
2011	na	866	210	24	1485	521	36

* data collected before the grazing trial was implemented; ** the gauge was damaged this wet season and therefore the sediment load is considered to be an underestimate. na = no cloud free days available for image capture

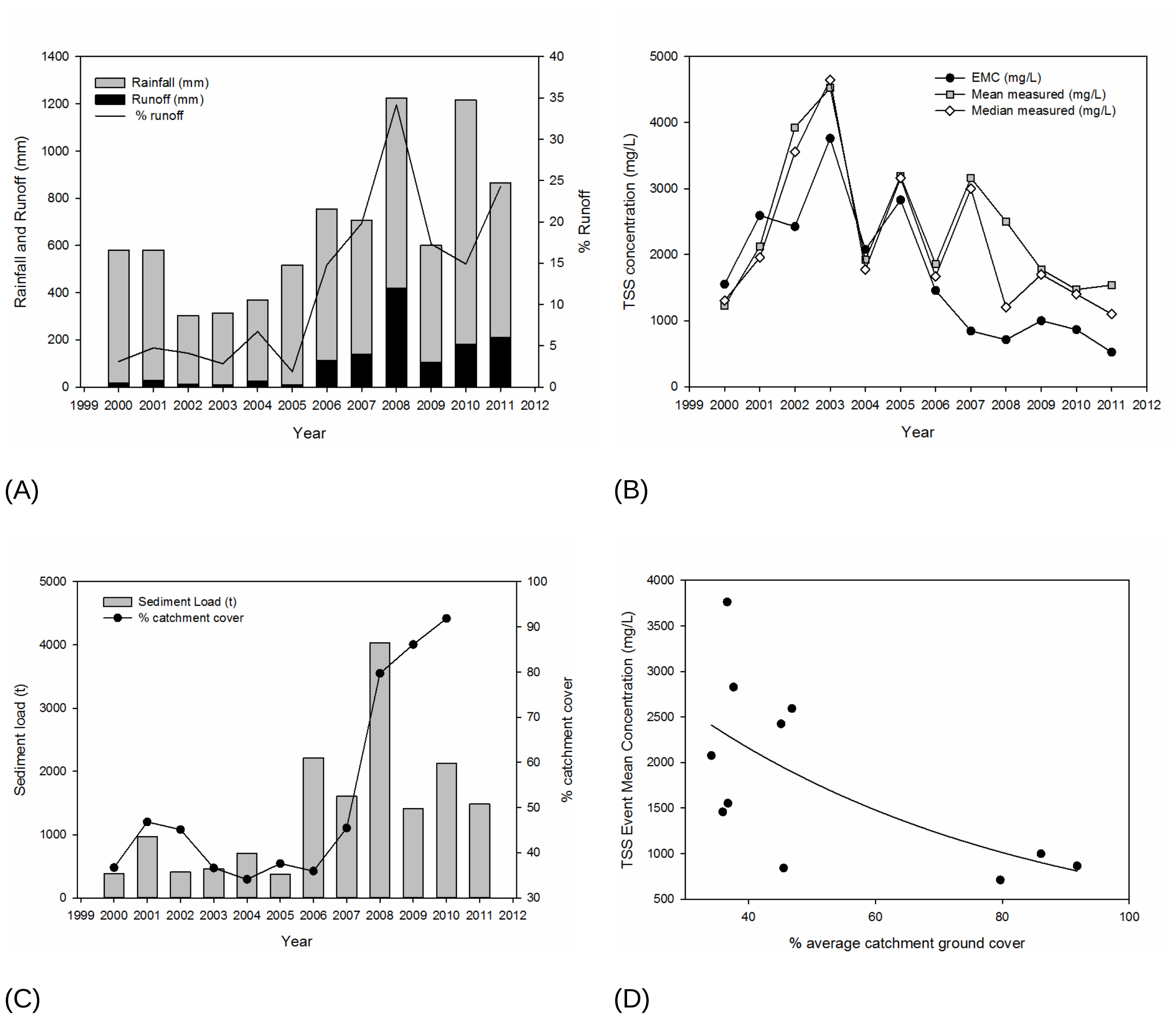


Figure 11: (A) Rainfall (mm), runoff (mm) and % runoff at the Weany Creek gauge between 2000 and 2011; (B) Event mean concentration (EMC), mean and median TSS concentration; (C) total sediment loads and average catchment cover measured between 2000 and 2011; and (D) the relationship between % average catchment ground cover and TSS event mean concentration (mg/L) measured at the stream gauge.

5 Discussion and conclusions

This report is a summary of a 10-year field trial that evaluated the effect of improved grazing management on vegetation cover, water and sediment loss from hillslopes and at the end of a 14 km^2 dry-tropical rangeland catchment. The study was initiated in a period of very low rainfall, however, the average annual rainfall for the 10 year study was slightly higher than the long term average for the area.

Over the 10 years, ground cover increased by ~46% on the instrumented hillslopes and over the whole catchment. Based on a comparison with a control property that did not undergo changed grazing management, ~16% (in absolute terms) of this cover increase may reflect the influence of changed grazing practices. It is important to note, however, that some proportion of this 16% cover difference is likely due to the variability between the two sites. The remaining cover improvement (~30% in absolute terms) is due to increasing rainfall during the study. Without a longer pre-treatment data set for the two properties (as presented in Thornton et al., 2007) the inferred influence of changed grazing practices should be treated as approximate. It may well be that grazing practices would have had a larger influence if the later years of the study had been less favourable for pasture growth. This suggests that the 20% increases in groundcover estimated by erosion modelling as required for achieving a 20% reduction in sediment yield to the GBR (Thorburn and Wilkinson, In Press) may be possible, provided the higher cover levels can be maintained during future dry periods. This is when the benefits of improved grazing practices are likely to be fully expressed.

Pasture biomass and condition also increased over the study. Biomass increased from an unsustainably low 60–400 kg of dry matter/ha in the early years of the study to 500–1,200 kg/ha in later years. Most of this cover improvement came from the stoloniferous grass Indian Couch, however, the percentage representation of the decreaser native perennial grasses in the total biomass increased from 5–7% to 15–30% across all flume sites, reaching 100-270 kg/ha in the later high-rainfall years. The proportion of litter and native perennial grasses that have a larger and deeper root structure are considered important for reducing runoff and erosion at the hillslope scale (Ludwig et al., 2005).

Numerous studies in the Burdekin and elsewhere have demonstrated that improved cover results in improved infiltration of water into the soil (Amiri et al., 2008; McIvor et al., 1995; Roth, 2004; Scanlan et al., 1996; Silburn et al., 2011). At Virginia Park, improved cover has been shown to be effective at reducing runoff for early wet season events via increased infiltration (Bartley et al., 2010a), however, high rainfall years continue to result in high annual runoff totals regardless of the amount of ground cover, and further decreases in annual runoff are going to be related to the ability of the soil to store water. The total annual runoff is largely controlled by the storage capacity of the soil profile, and the lack of response in annual runoff indicates that the storage capacity has not changed significantly. Data presented in Bartley et al., (2010a) suggests that hillslope runoff increases considerably following ~250 mm of rainfall, even with high cover levels (~70%). Given that the soils in the Weany Creek catchment are relatively old and highly weathered (by global standards) it is likely that the potential soil moisture store was only ever ~ 300 mm prior to grazing. Given there has been considerable loss of top-soil at this site over the last 100 years, recovery of the soil profile will be challenging, however, improvements may be possible if additional organic matter can be incorporated into the soil (via litter incorporation), macroporosity of the soil can be improved (via macro-fauna) and surface seals are removed that developed when the soil was bare. Even if these changes occur, improvements to pasture and macro-fauna are shown to be most effective only in the top 10 cm of the soil (Drewry, 2006). Recovery of soil condition and associated runoff has been demonstrated and can take as little as 3 years (Sartz and Tolsted, 1974), however, periods of 5-40 years are more likely where the soil has been severely compacted or previously cultivated (Connolly et al., 1998). Where there has been dramatic change in vegetation or severe soil degradation, ~60 years are needed to see changes in catchment runoff following improved soil condition (Wilcox et al., 2008). Importantly, in very large events (>100 mm and >45 mm/hr intensity), cover has been shown to have little or no effect on runoff (McIvor et al., 1995). Thus, it is unlikely that improved grazing land management will have an influence on the amount of runoff in very large events. If current cover levels (of 60-70%) are maintained at this site, and the proportion of native deep rooted perennial grasses are increased (to >50%), it may be possible that there will be further reductions in runoff from small to medium events in the next 30-40 years.

Bartley et al., (2010a) presented 6 years of data from these sites suggesting that there was a 70% decline in sediment yields from two out of three hillslopes in response to changed grazing management. A further 4 years of data have shown that the grazing practices have not resulted in a yield reduction independent of rainfall amount, and that rainfall remains a strong determinant of annual sediment yield. Thus we do not have definitive evidence that the hillslope sediment yield reductions, which standard erosion models such as the RUSLE (Renard et al., 1997) would associate with higher cover levels, have occurred in this study.

Despite there not being an identifiable change in annual hillslope runoff or sediment yields with improved grazing and ground cover, there has been a statistically significant reduction in TSS concentration on hillslopes that do not have large bare (<10% cover) areas connecting hillslopes to stream lines. The TSS concentrations from the 2 out of 3 flume hillslopes were not significantly different from data collected at sites with minimal grazing pressure when the ground cover reached ~70%. This suggests that if average ground cover in similar rangeland environments can be maintained at or near 70% over the long term, then TSS concentrations are likely to be minimised. Similar cover thresholds have been observed elsewhere (e.g. Castillo et al., 1997; Sanjari et al., 2009), noting that the amount of cover required to reduce and minimise TSS concentrations and soil loss will also depend on the soil type, rainfall intensity and antecedent soil moisture (Castillo et al., 2003; Silburn et al., 2011). It is also likely that couch (*Bothriochloa Pertusa)* dominated landscapes are going to need higher surface cover levels to help compensate for their lower below ground biomass levels compared to native tussock grasses, and increasing the proportion of native deep rooted perennial grasses should be an on-going target in these landscapes.

This study has also shown that average cover is not necessarily the best indicator of the water quality benefit of improved grazing management, and the spatial arrangement, species composition, structure and biomass are all critically important for accurately estimating the influence of cover on runoff and erosion. Areas with large bare patches can have erosion rates up to 70 times higher than areas without bare/scalded areas and the total erosion rates (of 0.25 mm/yr) for these sites are much greater than the soil production rates documented in the literature (Bui et al., 2011). While some reductions in TSS concentration have resulted from reduced utilisation, recovery in pasture composition and soil condition, with associated changes in infiltration and water quality, have only just begun at the Weany Creek site.

The catchment scale data followed a similar pattern to the flume results with runoff and sediment yields increasing during the study in response to increasing rainfall. The TSS concentrations had a weaker, but still significant decline in response to increasing ground cover in the catchment. This weaker relationship is expected as gully and bank erosion (together described as channel erosion) contribute to ~60% of the sediment concentrations and loads measured at the end of the catchment (Bartley et al., 2007; Wilkinson et al., 2012). Although channel erosion is indirectly influenced by hillslope ground cover, there is likely to be a lag in this response, and there are other processes (e.g. channel bed incision and widening) that are likely to be involved that do not respond to ground cover changes. It is also important to note that although the ground cover changes that have occurred at this site are considerable, the biomass levels are still lower than those recommended by Ash et al., (2011) for this landscape type. Therefore further reductions in sediment concentrations may be possible if the proportion of decreaser native perennial grasses (DNPG) continue to increase and start to dominate the species composition in these landscapes.

This study has shown that appropriate grazing land management can increase ground cover which, in turn, can reduce sediment concentrations, but not necessarily runoff or sediment loads from hillslopes and small (~14 km^2) rangeland catchments. The specific quantitative impact that improved ground cover has on catchment TSS concentrations is difficult to evaluate at the catchment scale due to the contribution from other processes such as gully and bank erosion. Catchment modelling would be a potential tool to scale these local data to larger catchment areas, however, many of the available models do not allow for temporal lags between applied management actions and a water quality response.

This study has highlighted that more research is needed to identify practical methods for managing persistent low cover areas adjacent to stream lines in rangeland areas, and to better understand the pasture composition response to reduced utilisation and wet-season rest. This study has also highlighted the importance of long term well managed data sets for identifying the link between land management change, land condition and water quality response. The results of this research are likely to be important for managing expectations with respect to water quality target setting, catchment water quality modelling and land management evaluation in the Great Barrier Reef catchments and in other rangeland environments.

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