Paddock scale water quality monitoring of grazing management practices in the Fitzroy Basin

Technical report on the effect of grazing pressure on water quality for the 2015 to 2018 hydrological years

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Cover photographs: cattle in the heavily grazed pasture catchment (left); runoff event through a monitoring flume (centre); and a fenceline comparison of conservatively and heavily grazed pastures (right). All photographs are sourced from the Brigalow Catchment Study photo archives, courtesy of the Department of Natural Resources, Mines and Energy.

This report is available from the Brigalow Catchment Study website
www.brigalowcatchmentstudy.com.

Executive Summary

Loss of sediment, particulate nitrogen and particulate phosphorus in runoff from the extensive grazing lands of the Fitzroy Basin, central Queensland, continue to contribute to the declining health of the Great Barrier Reef. Substantial investment has been made by the Australian and Queensland Governments to improve runoff water quality from grazing lands; however, there is little data directly comparing the effect of grazing pressure on hydrology and water quality. This is further confounded by the difficulty of separating the impacts of climate variability from the anthropogenic impacts of changing land use from native vegetation to grazing. This study measured changes in hydrology, water quality, ground cover and pasture biomass from conservative and heavy cattle grazing pressures on rundown (>30 years old) improved grass pastures. It also considered the anthropogenic effect of changing land use from brigalow scrub to an improved grass pasture with a conservative grazing pressure. The paddock-scale (12.0 to 16.8 ha) study was conducted at the long-term Brigalow Catchment Study, located in the Fitzroy Basin of central Queensland, Australia.

Conservative grazing pressure averaged 5.9 ha/AE, which was a lighter stocking rate than the calculated safe long-term carrying capacity of 3.4 ha/AE for the rundown pasture. This was due to below average rainfall which limited pasture growth over the four hydrological years of this study (October 2014 to September 2018). Mean annual rainfall at the study site ranged from 272 mm in 2017 to 584 mm in 2018, which was well below the long-term average of 648 mm. Heavy grazing pressure averaged 1.9 ha/AE, which reflected stocking rates recommended for newly established buffel grass pasture rather than for rundown pasture.

Heavy grazing resulted in 3.6 times more total runoff compared to conservative grazing (18.8 mm/yr cf. 5.2 mm/yr) and 3.3 times greater average peak runoff rate (2.9 mm/hr cf. 0.9 mm/hr). No runoff occurred from brigalow scrub in two of the four years, which means that no runoff would have occurred from the conservatively grazed pasture had it remained uncleared. Runoff from the conservatively grazed pasture in these two years was an absolute anthropogenic increase attributable to land use change.

Runoff loads of total suspended solids and total, particulate and dissolved nitrogen and phosphorus were greater from the two grass pastures than from brigalow scrub, while loads from heavy grazing were greater than from conservative grazing. Heavy grazing resulted in 3.2 times greater load of total suspended solids than from conservative grazing (46 kg/ha/yr cf. 14 kg/ha/yr), 1.6 times greater load of total nitrogen (0.46 kg/ha/yr cf. 0.29 kg/ha/yr) and 2.6 times greater load of total phosphorus (0.10 kg/ha/yr cf. 0.04 kg/ha/yr). Total nitrogen and phosphorus loads from grass pastures had substantial contributions of both particulate and dissolved fractions regardless of grazing pressure, and the dominant fraction varied between years. Particulate and dissolved loads of nitrogen and phosphorus from heavily grazed pasture were between 1.4 and 3.7 times greater than from conservatively grazed pasture. In the two years with no runoff from brigalow scrub, water quality loads from the conservatively grazed pasture were also an absolute anthropogenic increase. In contrast to loads, event mean concentrations for all water quality parameters were lower from heavy than conservative grazing due to the dilution effect of increased runoff.

At the commencement of this study, the conservatively and heavily grazed pastures started in a similar condition with a comparable proportion of bare ground (12.3% cf. 13.4%) and pasture biomass (6.9 t/ha cf. 6.2 t/ha). After four below average rainfall years, heavy grazing of rundown pasture resulted in 2.5 times more bare ground than the conservatively grazed pasture (14.9% cf. 5.9%) and only 8% of the pasture biomass (0.4 t/ha cf. 5.3 t/ha).

A safe long-term carrying capacity for rundown buffel grass pasture established on predominantly clay soils, previously dominated by brigalow scrub, was 3.4 ha/AE. Exceeding the safe long-term carrying capacity during this four year study increased runoff and subsequently increased loads of total suspended solids in runoff. Loads of total, particulate and dissolved nitrogen and phosphorus in runoff also increased under heavy grazing pressure. Ground cover and pasture biomass are both indicators of land condition and decreased under heavy grazing pressure. This study compliments other research that has reported improved land condition and reduced economic risk after transitioning from heavy to conservative grazing pressure. Thus, conservative grazing pressure is a realistic option for landholders to improve land condition, business profitability and runoff water quality.

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AE/ha/yr	Adult equivalent per hectare per year
cf.	Confer or compare with
days/yr	Days per year
ha	Hectare
ha/AE	Hectare per adult equivalent
ha/AE/yr	Hectare per adult equivalent per year
ha/head	Hectare per head
kg	Kilogram
kg/ha	Kilogram per hectare
kg/ha/yr	Kilogram per hectare per year
kg/head	Kilogram per head
m	Metre
m^2	Square metre
mg/L	Milligram per litre
Mha	Million hectare
mm	Millimetre
mm/hr	Millimetres per hour
mm/yr	Millimetres per year
t/ha	Tonne per hectare

Abbreviations

AMC	Annual Mean Concentration
BCS	Brigalow Catchment Study
C1	Catchment 1; virgin brigalow scrub which is an ungrazed control
C3	Catchment 3; grass pasture with conservative grazing pressure
C5	Catchment 5; grass pasture with heavy grazing pressure
DIN	Dissolved Inorganic Nitrogen
DIP	Dissolved Inorganic Phosphorus, also known as Filterable Reactive Phosphorus (FRP) and Orthophosphate (PO_4-P)
DON	Dissolved Organic Nitrogen
DOP	Dissolved Organic Phosphorus
EMC	Event Mean Concentration
NH_4-N	Ammonium-Nitrogen
NO_x-N	Oxidised Nitrogen
PN	Particulate Nitrogen, also known as Total Suspended Nitrogen (TSN)
PP	Particulate Phosphorus, also known as Total Suspended Phosphorus (TSP)
TDN	Total Dissolved Nitrogen
TDP	Total Dissolved Phosphorus
TN	Total Nitrogen
TP	Total Phosphorus
TSS	Total Suspended Solids

Acknowledgments

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1 Introduction

The 2017 scientific consensus statement on Great Barrier Reef water quality identified the Fitzroy Basin as a high priority area for reducing fine sediment and particulate nutrients (Waterhouse *et al.* 2017). Grazing is the dominant land use in this region, with more than 2.6 million cattle over 11.1 Mha (Australian Bureau of Statistics 2009; Meat and Livestock Australia 2017). This is the largest cattle herd in any natural resource management region in both Queensland and Australia, accounting for 25% of the state herd and 11% of the national herd (Meat and Livestock Australia 2017). The 2016 Great Barrier Reef report card noted that only 29% of grazing in the Fitzroy Basin was under best management practices compared to the 90% target (The State of Queensland 2017a). Progress to reduce anthropogenic end-of-catchment loads for this region was classed as very poor due to reductions of only 9.6% for sediment, 4.7% for particulate nitrogen and 8.5% for particulate phosphorus compared to the 20% targets. This is despite greater reductions in sediment and particulate nutrients compared to the prior year, which was mainly achieved by excluding cattle from streambanks in high risk areas (The State of Queensland 2017b).

In contrast, the Burdekin Basin had sediment reductions of 17.7% which was attributed to management practices such as pasture budgeting to determine carrying capacity and the adoption of wet season spelling (The State of Queensland 2017b). These practices are commonly recommended to maintain or improve ground cover (Jones *et al.* 2016; Moravek *et al.* 2017; O'Reagain *et al.* 2011), as high cover is known to reduce runoff, and hence also sediment and nutrients exported in runoff (Murphy *et al.* 2008; Nelson *et al.* 1996; Schwarte *et al.* 2011; Silburn *et al.* 2011). For example, in the Burdekin Basin, O'Reagain *et al.* (2008) compared a light stocking rate which had 20 to 25% pasture utilisation to a heavy stocking rate which had 40 to 50% pasture utilisation. In below average rainfall years, the heavy stocking rate had less ground cover, a greater frequency and intensity of runoff, and higher sediment concentrations in runoff. However, there was little difference between the two stocking rates in high rainfall years due to high ground cover (O'Reagain *et al.* 2008).

Moravek *et al.* (2017) reviewed economic literature on grazing management practices and found that there is not always a win-win situation between business profitability and environmental outcomes, such as reduced sediment in runoff. This is possibly the reason that so few landholders use the recommended practices of reduced stocking rates and wet season spelling. For example, of the total area mainly used for grazing in Queensland, only 6% (7.4 Mha) is under tactical grazing which involves a range of management practices to meet various animal and pasture objectives (Australian Bureau of Statistics 2017). Furthermore, 25% of Queensland agricultural businesses that mainly used land for grazing did not spell pasture between grazing periods (Australian Bureau of Statistics 2017). Although spelling pasture has been shown to increase biomass, seasonal conditions can actually have a stronger effect on ground cover and pasture biomass (Jones *et al.* 2016). This further highlights the importance of managing grazing pressure to maintain landscape resilience, particularly during periods of below average rainfall (Edwards 2018).

This study provides more evidence for adopting the recommended management practices of a safe long-term carrying capacity and wet season spelling for improved water quality outcomes by:

(1) Quantifying the impact of conservative and heavy grazing pressure on ground cover, pasture biomass, hydrology, and both loads and event mean concentrations (EMCs) of total suspended solids, nitrogen and phosphorus in runoff over four hydrological years (2015 to 2018); and

(2) Determining the anthropogenic impact of grazing by comparing hydrology and both loads and event mean concentrations (EMCs) of total suspended solids, nitrogen and phosphorus in runoff from a conservatively grazed pasture to virgin brigalow scrub, which is representative of the pre-European landscape.

2 Methods

2.1 Site Description

The Brigalow Catchment Study (BCS) is a paired, calibrated catchment study located (24°48'S and 149°47'E) near Theodore in central Queensland, Australia. It was established in 1965 to quantify the impact of land development for agriculture on hydrology, productivity and resource condition (Cowie *et al.* 2007). The study site was selected to represent the Brigalow Belt bioregion which covers an area of approximately 36.7 Mha from Townsville in north Queensland to Dubbo in central-western New South Wales (Thornton *et al.* 2007) (Figure 1). In its native state, the site was dominated by brigalow (*Acacia harpophylla*), either in a monoculture or in association with other species, such as belah (*Casuarina cristata*) and Dawson River blackbutt (*Eucalyptus cambageana*) (Johnson 2004). The extant uncleared vegetation of the BCS is classified as regional ecosystems 11.4.8, woodland to open forest dominated by *Eucalyptus cambageana* and *Acacia harpophylla*, and 11.4.9, open forest and occasionally woodland dominated by *Acacia harpophylla* (Queensland Government 2014). Slope of the land averages 2.5% (1.8% to 3.5%) and soils are an association of Vertosols, Dermosols, Sodosols and Chromosols. These soil types are representative of 75% of the Fitzroy Basin under grazing: 28% Vertosols; 28% Sodosols; 11% Dermosols; and 8% Chromosols (Roots 2016). The region has a semi-arid, subtropical climate and mean annual hydrological year (October 1965 to September 2018) rainfall at the site was 648 mm.

2.2 Long-Term Brigalow Catchment Study

The BCS can be separated into four experimental phases: (1) calibration of three catchments in an uncleared state from 1965 to 1982; (2) development of two catchments for agriculture from 1982 to 1983; (3) comparison of cropping and grazing land use to virgin brigalow scrub from 1984 to 2010; and (4) a comparison of leguminous and non-leguminous pastures to virgin brigalow scrub during the adaptive land management phase from 2010 to 2014 (Table 1). The adaptive land management phase involved the transition of the cropping catchment into a grazed ley pasture to improve soil fertility, and the addition of two new catchments; a grazed leucaena-grass pasture and a heavily grazed grass pasture. This phase continued from 2015 to 2018, but with a focus on comparing improved grass pasture with conservative and heavy grazing pressures to virgin brigalow scrub.

The 18 year calibration period for the three long-term catchments in Stage I means that runoff characteristics from the original cropping and grazing catchments can be estimated had they remained brigalow scrub. A calibration period for the two new catchments was not possible as they had been developed for agriculture sometime between 1965 and 1969, which was 40 to 50 years prior to their inclusion in the study. Thus, although the two new catchments have their own unique hydrological characteristics, their relationship to the three long-term catchments in an uncleared state is unknown. Further details on these experimental phases are documented in other sources (Cowie *et al.* 2007; Radford *et al.* 2007; Thornton *et al.* 2007; Thornton and Elledge 2013).

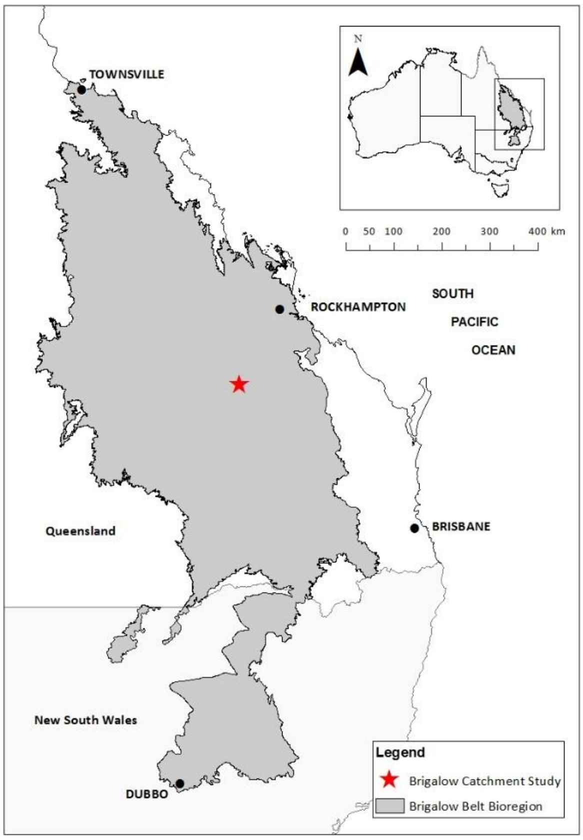

Figure 1: Location of the Brigalow Catchment Study within the Brigalow Belt bioregion of central Queensland.

Table 1: Land use history of the Brigalow Catchment Study.

Catchment	Land use by experimental stage			
	Stage I **Jan 1965 to Mar 1982**	**Stage II** **Mar 1982 to Sep 1983**	**Stage III** **Sep 1984 to Jan 2010**	**Stage IV** **Jan 2010 to Present (2018)**
C1	Brigalow scrub	Brigalow scrub	Brigalow scrub	Brigalow scrub
C2	Brigalow scrub	Development	Cropping	Ley pasture
C3	Brigalow scrub	Development	Grass pasture	Grass pasture
C4	NA	NA	NA	Leucaena pasture[1]
C5	NA	NA	NA	Grass pasture[2]

[1] *Monitoring in the C4 leucaena pasture commenced in 2009.*

[2] *Monitoring in the C5 grass pasture commenced in 2014.*

2.3 Treatments

Although all five catchments described above were continually monitored as part of the long-term BCS, this report only considers the conservatively grazed pasture (Catchment 3), the heavily grazed pasture (Catchment 5) and the brigalow scrub (Catchment 1) land uses (Figure 2; Table 2). The period of reporting is from the adaptive land management phase for the 2015 to 2018 hydrological years (October 2014 to September 2018). All references to years are based on hydrological years.

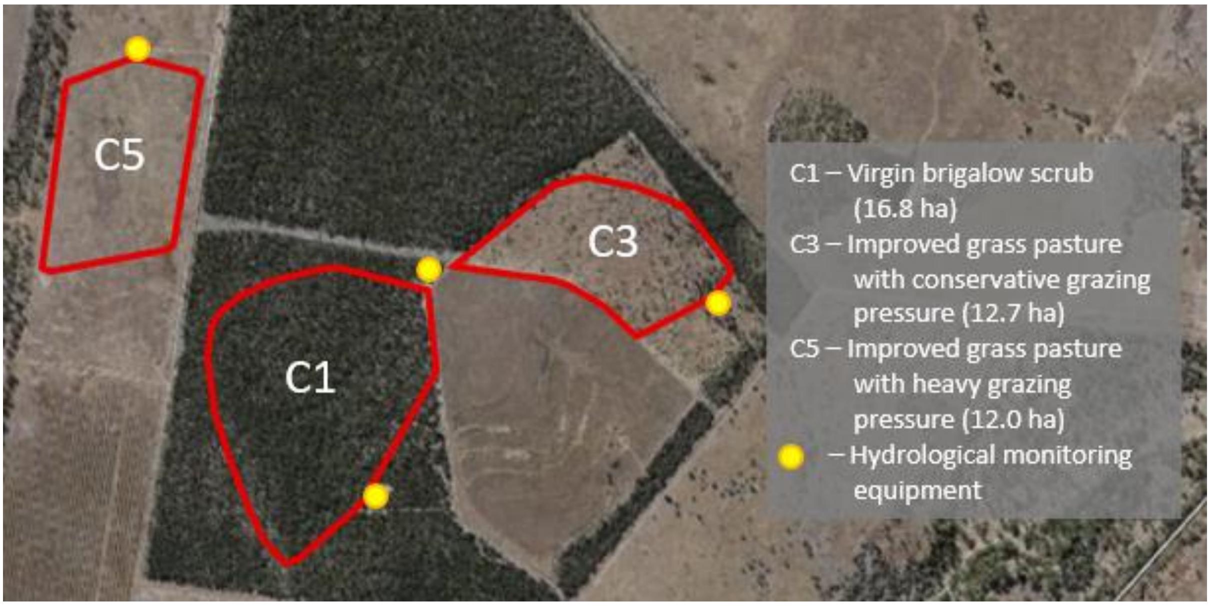

Figure 2: Aerial photo of the Brigalow Catchment Study showing the hydrological (runoff) boundaries and location of monitoring equipment within the three catchments.

The brigalow scrub catchment was retained in its virgin uncleared condition. This was an ungrazed control treatment representative of the Brigalow Belt bioregion in its pre-European condition. This catchment has Vertosols and Dermosols (clay soils) covering approximately 70% of the hydrological area and Sodosols over the remaining 30% (Cowie *et al.* 2007). The conservatively grazed catchment was a buffel grass (*Cenchrus ciliaris* cv. Biloela) pasture. This catchment has Vertosols and Dermosols (clay soils) covering approximately 58% of the hydrological area and Sodosols over the remaining 42% (Cowie *et al.* 2007). The heavily grazed catchment was a purple pigeon grass (*Setaria incrassata*) and buffel grass (*Chenchrus ciliaris*) pasture. This catchment has Vertosols covering approximately 90% of the hydrological area and Chromosols over the remaining 10% (unpublished BCS data).

The two pastures were spelled prior to the commencement of this study in October 2014. The conservatively grazed pasture was spelled between September 2011 and October 2014, with the exception of grazing between December 2013 and February 2014. The heavily grazed pasture was grazed from July 2012 to December 2012 and then spelled until October 2014. Stocking rates were set based on pasture biomass and have been converted to adult equivalents per hectare per year (AE/ha/yr) to account for differences in the size of cattle, and also the length of time the pastures were grazed (Table 3). Stocking rates in hectares per an adult equivalent (ha/AE) are also provided; however, this gives no indication of the time that the pasture was stocked. An adult equivalent is equal to a 450 kg non-lactating animal. Recommended stocking rates are about 2 ha/head for newly established buffel grass pasture and about 3 ha/head for rundown buffel grass pasture, which can occur in as little as five to ten years after establishment (Noble *et al.* 2000; Peck *et al.* 2011). Spelling was defined as the number of days annually that pasture wasn't grazed (Table 4). Overall, the conservatively grazed pasture had lower stocking rates and greater periods of spelling.

Table 2: Description of the three Brigalow Catchment Study treatments reported for the 2015 to 2018 hydrological years.

Parameter	Brigalow scrub	Conservative grazing	Heavy grazing
Alternative catchment name	Catchment 1 or C1	Catchment 3 or C3	Catchment 5 or C5
Hydrological area (ha)	16.8	12.7	12.0
Total grazed area (ha)	0.0	17.0	25.0
Land use	Virgin brigalow scrub	Improved grass pasture	Improved grass pasture
Cattle stocking philosophy	Ungrazed control	Conservative stocking rate	High stocking rate
Pasture spelling philosophy	Ungrazed control	Wet season spell	Limited spelling
Pasture biomass philosophy	Not applicable	Minimum 1,000 kg/ha	No minimum limit
Photo			

Table 3: Annual stocking rates in adult equivalents (AE) per hectare per year and also in hectare per AE for the two pastures.

Year	Stocking rate (AE/ha/yr)		Stocking rate (ha/AE)	
	Conservative grazing	Heavy grazing	Conservative grazing	Heavy grazing
2013	Destocked	0.09	Destocked	1.89
2014	0.19	Destocked	0.67	Destocked
2015	0.20	0.83	3.86	0.81
2016	0.13	0.20	1.47	1.32
2017	0.19	0.26	4.42	1.11
2018	Destocked	0.86	Destocked	0.51

Table 4: Annual number of non-grazed days (spelling) for the two pastures.

Year	Pasture spelled (days/yr)	
	Conservative grazing	Heavy grazing
2013	365	303
2014	320	365
2015	80	33
2016	297	286
2017	76	180
2018	365	146

2.4 Hydrology

Rainfall and runoff were monitored over four hydrological years from October 2014 to September 2018. Rainfall was measured using a 0.5 mm tipping bucket rain gauge located at the head point of the three long-term catchments (Thornton *et al.* 2007). Each catchment was instrumented to measure runoff using a 1.2 m steel HL flume with a 3.9 x 6.1 m approach box. Water heights through the flume were recorded using a pressure transducer with a mechanical float recorder backup. Stage heights were converted to discharge using a rating table (Brakenseik *et al.* 1979), while peak runoff rate was calculated on an event basis from instantaneous peak height. A runoff event commenced when stage height exceeded zero and finished when it returned to zero. Further details on calculating total runoff and peak runoff rates are documented in other sources (Thornton *et al.* 2007; Thornton and Yu 2016).

2.5 Water Quality

Discrete water quality samples were obtained over four hydrological years (October 2014 to September 2018) using an auto-sampler located at the flume of each catchment. Auto-samplers were programmed to sample every 0.1 m change in stage height. Laboratory analyses of runoff samples were undertaken by Queensland Health Forensic and Scientific Services (Table 5), with some parameters calculated by difference (Table 6).

Table 5: Methods used by Queensland Health Forensic and Scientific Services for total suspended solids and nutrient analyses of runoff water samples.

Parameter	Method
TSS	Method 18211 based on gravimetric quantification of solids in water
TN / TDN	Method 13802 by simultaneous persulfate digestion
NO_x-N	Method 13798 based on flow injection analysis of nitrogen as oxides
NH_4-N	Method 13796 based on flow injection analysis of nitrogen as ammonia
TP / TDP	Method 13800 by simultaneous persulfate or Kjeldahl digestion
DIP	Method 13799 by flow injection analysis

Table 6: Equations used to estimate nutrient parameters that were not directly measured.

Parameter	Equation
PN	TN - TDN
DON	TDN - DIN
DIN	NO_x-N + NH_4-N
PP	TP - TDP
DOP	TDP - DIP

Event based water quality loads were calculated by dividing the hydrograph into sampling intervals, multiplying the discharge in each interval by the sample concentration, and summing the resulting loads from all intervals. The intervals were defined as the start of flow to the midpoint of sample one and sample two, the midpoint of sample one and sample two to the midpoint of sample two and sample three, and so on. Total annual load was calculated by summing all of the event based water quality loads, and load in kg/ha was calculated by accounting for hydrological catchment area.

Event based EMCs were calculated by dividing total event load by total event flow, and mean annual EMCs were calculated by averaging the event based EMCs within each year. Mean annual EMCs from 2000 to 2018 were used to calculate a long-term EMC for each catchment. The method used for calculating a mean annual EMC is described in Appendix 1. Where water quality data was not captured due to flows being too small to trigger auto-samplers, load estimations were obtained by multiplying the long-term EMC by observed flow. Only observed (measured) event based EMCs were included in the calculation of mean annual EMCs.

Dominant pathways of nitrogen and phosphorus loss in runoff were determined by the proportion of particulate and total dissolved fractions. That is, if total dissolved nitrogen was greater than 60% of total nitrogen it was considered to be transported primarily in a dissolved phase, and if less than 40% it was transported primarily in a particulate phase. If the value was between 40% and 60%, it was considered to have no dominant pathway of loss. The same method was applied to total phosphorus and total dissolved phosphorus.

2.6 Ground Cover

Ground cover from the total grazed area of the two pasture catchments, excluding the shade lines, was compared from October 2012 to April 2018 using VegMachine® (Fitzroy Basin Association 2018). This is an online tool that uses satellite imagery to summarise spatial and temporal changes in cover; that is, cover at or near ground level which excludes higher cover such as tree and shrub canopies. Seasonal deciles were also reported for total (green and non-green) cover, where total cover and bare ground equal 100%. Quarterly data from Autumn (March to May) 1988 to Summer (December to February) 2012/2013 are used as a baseline, and then every season is ranked (expressed as a decile) against all corresponding values for that season in the baseline period (Trevithick 2017). For example, total cover from spring (September to November) 2013 is ranked against total cover in all the spring images from the baseline period.

2.7 Pasture Biomass

The BOTANAL method of Tothill *et al.* (1978) was used to estimate pasture biomass one to two times per year over the total grazed area of the two pasture catchments, excluding the shade lines. Pasture assessments occurred in the late wet and/or the late dry season. The late wet season is typically the end of the pasture growing season, and the late dry season provides an indicator of the remaining pasture available for cattle grazing until suitable conditions for growth occur. Pasture biomass was visually estimated for up to 300 0.16 m^2 quadrats in each catchment at each sampling period. Visual estimates were calibrated against a set of 10 quadrats which were cut, dried and weighed.

2.8 Qualitative Pasture Assessments

A photographic comparison of the conservatively and heavily grazed pastures during the late wet and late dry seasons over the 2015 to 2018 hydrological years is also provided. This is to help the reader visualise how ground cover and pasture biomass measurements appear in the field. BOTANAL measurements of pasture biomass and photographs may have occurred at different times within the season.

During July 2018, a visual comparison of pasture condition was also made between the conservatively and heavily grazed pastures of the BCS with five other heavily grazed properties under different ownership elsewhere in the Fitzroy Basin.

3 Results

3.1 Hydrology

Total annual rainfall at the study site was below the long-term mean annual rainfall of 648 mm (October 1965 to September 2018) in all four hydrological years (Figure 3). Rainfall was in the 31st percentile in 2015 (563 mm), the 29th percentile in 2016 (562 mm), the lowest on record in 2017 (272 mm) and in the 40th percentile in 2018 (584 mm).

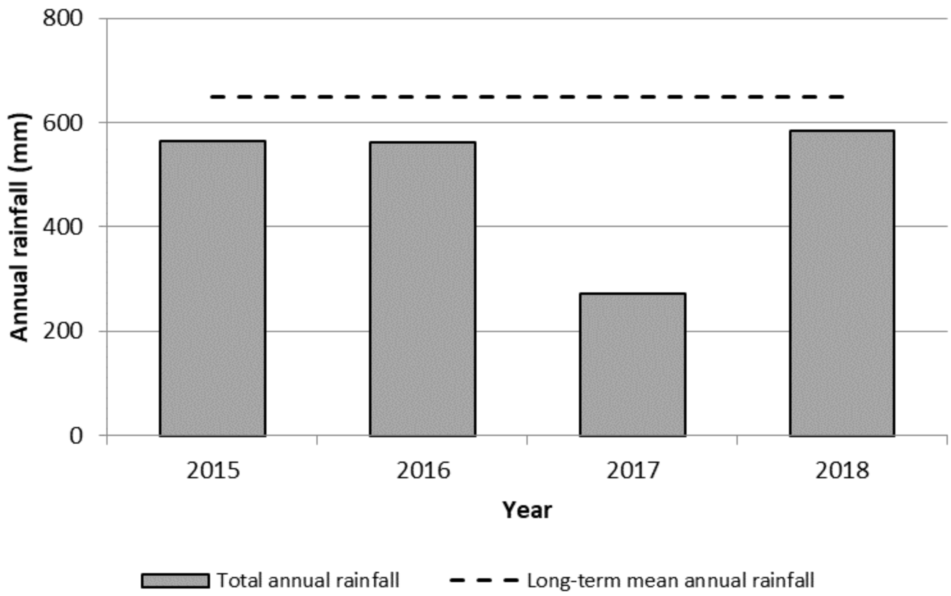

Figure 3: Total annual hydrological year rainfall for 2015 to 2018 relative to the long-term mean annual rainfall for the Brigalow Catchment Study.

Similar to rainfall, runoff for the four hydrological years was below the long-term mean annual runoff (1985 to 2018) for the brigalow scrub and conservatively grazed catchments (Figure 4). The heavily grazed catchment was only instrumented in 2014, at the commencement of this study, and mean annual runoff was based on four years (2015 to 2018) data. Runoff from brigalow scrub was in the 32nd percentile in 2015, no runoff occurred in 2016 and 2017, and in 2018 was in the 29th percentile. Runoff from the conservatively grazed catchment was in the 35th percentile in 2015, the 30th percentile in 2016, no runoff occurred in 2017, and in 2018 was in the 15th percentile. The heavily grazed catchment had the same amount of runoff (28 mm) in both 2015 and 2016, no runoff occurred in 2017, and in 2018 runoff was 68% of the 2015 to 2016 average.

Hydrological data and water quality sampling effort for 2015 to 2018 are summarised in Table 7. Over the four hydrological years, there was a total of two events from the brigalow scrub catchment, four events from the conservatively grazed catchment, and five events from the heavily grazed catchment. Although the number of events and total runoff was low in these below average rainfall years, when runoff did occur, the heavily grazed catchment had consistently greater runoff than the conservatively grazed catchment. A similar trend was also observed for peak runoff rates with both average and maximum values greatest from the heavily grazed pasture.

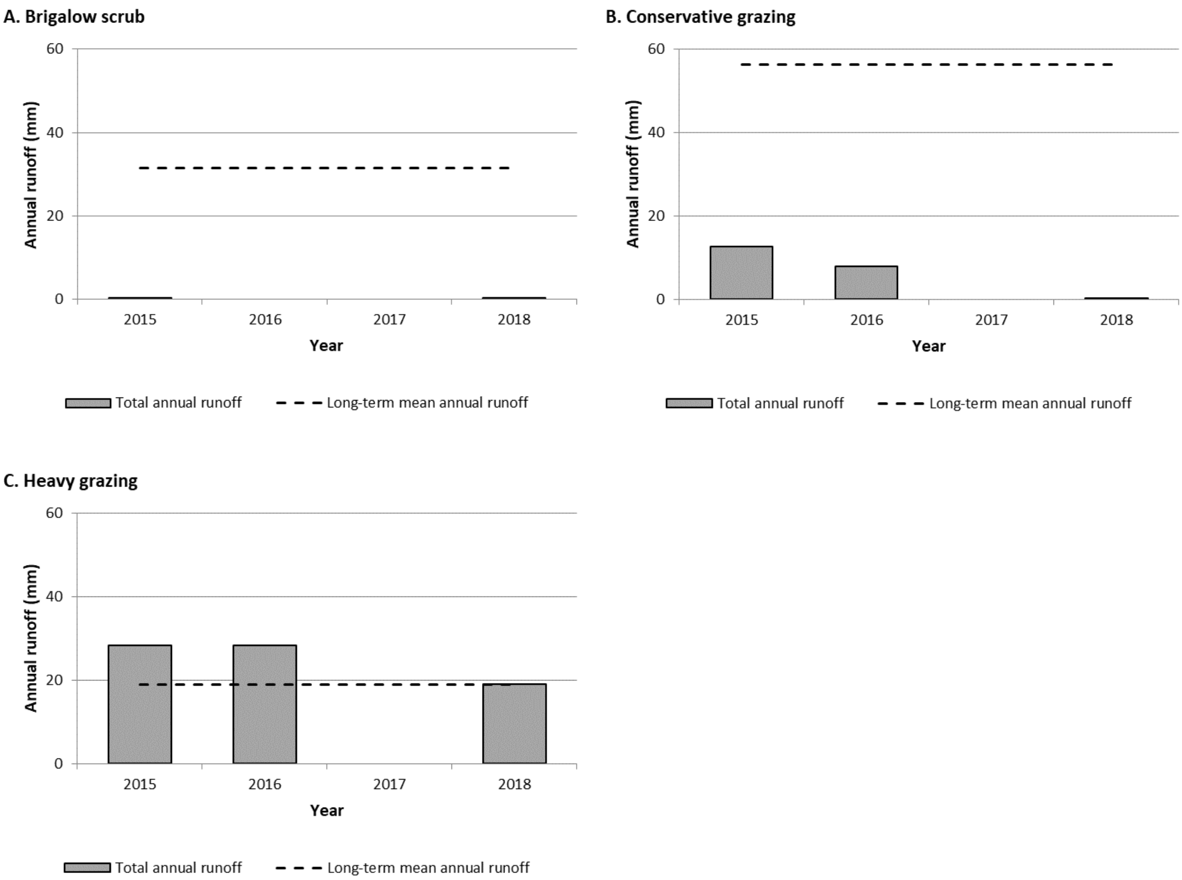

Figure 4: Total annual hydrological year runoff for 2015 to 2018 relative to the long-term mean annual runoff for the three catchments. Long-term means were based on 34 years (1985 to 2018) data for the brigalow scrub and conservatively grazed catchments, and four years data (2015 to 2018) for the heavily grazed catchment.

Using the hydrological calibration developed during Stage I (1965 to 1982), runoff characteristics for the conservatively grazed pasture (Catchment 3) can be estimated had it remained brigalow scrub (Table 8). In 2015, conservatively grazed pasture generated 65 times more total runoff and 13 times greater peak runoff than uncleared estimates for this catchment. As no runoff occurred from the brigalow scrub catchment (Catchment 1) in 2016 and 2017, there would have been no runoff from Catchment 3 in an uncleared state. Total runoff and peak runoff from the brigalow scrub and conservatively grazed pasture catchments were the same in 2018 (Table 7), which means that there were negligible difference between observed and estimated uncleared runoff from the conservatively grazed catchment in that year.

Table 7: Observed annual hydrological year summaries of runoff and sampling effort for three catchments.

Parameter	Year	Brigalow scrub	Conservative grazing	Heavy grazing
Number of events	2015	1	2	2
	2016	0	1	1
	2017	0	0	0
	2018	1	1	2
Number of samples	2015	0	3	21
	2016	0	2	6
	2017	0	0	0
	2018	0	0	4
Total runoff (mm)	2015	0.2	13	28
	2016	0	8	28
	2017	0	0	0
	2018	0.1	0.1	19
Average peak runoff rate (mm/hr)	2015	0.1	2.6	6.4
	2016	0	1.0	2.6
	2017	0	0	0
	2018	0.1	0.1	2.6
Maximum peak runoff rate (mm/hr)	2015	0.1	3.1	6.5
	2016	0	1.0	2.6
	2017	0	0	0
	2018	0.1	0.1	4.7

Table 8: Predicted annual hydrological year summaries of runoff from the conservatively grazed pasture catchment had it remained uncleared brigalow scrub.

Parameter	Year	Catchment 3
Estimated uncleared runoff (mm)	2015	0.2
	2016	0
	2017	0
	2018	0.1
Increase in runoff under pasture (mm)	2015	12
	2016	8
	2017	0
	2018	0
Estimated uncleared average peak runoff rate (mm/hr)	2015	0.2
	2016	0
	2017	0
	2018	0.4
Increase in average peak runoff rate under pasture (mm/hr)	2015	2.4
	2016	1.0
	2017	0
	2018	0

3.2 Water Quality

Loads and EMCs of total suspended solids, nitrogen and phosphorus are presented in Appendix 1. Results for 2015 are presented in Table A1, 2016 in Table A2 and 2018 in Table A3. There was no runoff, and hence no water quality from any catchment in 2017.

Loads of total suspended solids and all nitrogen and phosphorus parameters from heavily grazed pasture were between 1.4 and 3.7 times greater than from conservatively grazed pasture. In contrast, EMCs were consistently lower from heavily grazed pasture, being only 30% to 90% of that from conservatively grazed pasture. Loads of all water quality parameters from brigalow scrub were almost negligible due to no runoff in two of the four hydrological years, and less than 0.2 mm of runoff in the other two years. Consequently, no water quality samples were collected from this catchment and all data presented are estimations based on observed runoff and long-term EMCs. Using the hydrological calibration developed during Stage I (1965 to 1982), there would have been virtually no runoff from the conservatively grazed catchment in all four years had it remained brigalow scrub. Hence all loads of total suspended solids, nitrogen and phosphorus in runoff from the conservatively grazed catchment are an absolute anthropogenic increase attributable to changing land use from brigalow scrub to grazed pasture.

3.2.1 Total Suspended Solids

Mean annual load of total suspended solids from the heavily grazed pasture was 3.2 times greater than from the conservatively grazed pasture (Figure 5). The mean annual EMC for total suspended solids was 277.7 mg/L from conservatively grazed pasture and 234.7 mg/L from heavily grazed pasture.

Figure 5: Mean annual load of total suspended solids in runoff from 2015 to 2018.

3.2.2 Nitrogen

Mean annual load of total nitrogen from the heavily grazed pasture was 1.6 times greater than from the conservatively grazed pasture (Figure 6). Total nitrogen was composed of similar amounts of particulate and total dissolved nitrogen irrespective of grazing pressure; 49% and 51% for conservatively grazed pasture and 45% and 55% for heavily grazed pasture, respectively. Although there was limited data from brigalow scrub, estimations indicate a greater contribution of total dissolved nitrogen (64%) than particulate nitrogen (36%) towards total nitrogen. The dominant pathway of nitrogen loss was in a dissolved form from brigalow scrub, but was unclear for the two pasture catchments (Table 9). The mean annual EMC for total nitrogen was 6.5 mg/L from conservatively grazed pasture and 2.4 mg/L from heavily grazed pasture; particulate nitrogen was 3.4 mg/L and 1.1 mg/L; and total dissolved nitrogen was 3.1 mg/L and 1.2 mg/L, respectively.

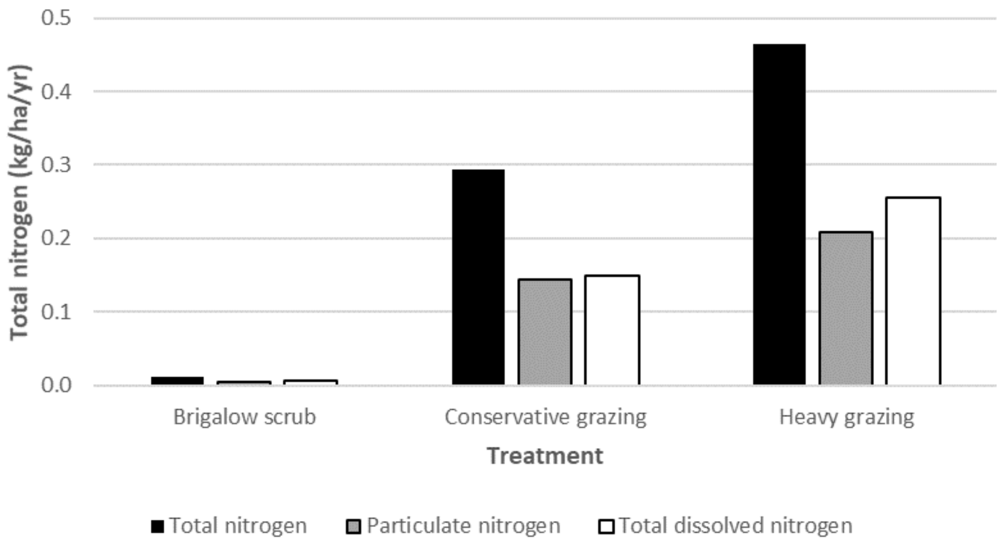

Figure 6: Mean annual load of total, particulate and dissolved nitrogen in runoff from 2015 to 2018.

Table 9: Dominant pathway of nitrogen loss in runoff from 2015 to 2018.

Year	Brigalow scrub	Conservative grazing	Heavy grazing
2015	Dissolved	No dominant	No dominant
2016	No runoff	No dominant	Dissolved
2017	No runoff	No runoff	No runoff
2018	Dissolved	Dissolved	Particulate

Mean annual load of total dissolved nitrogen from the heavily grazed pasture was 1.7 times greater than from conservatively grazed pasture (Figure 7). Dissolved organic and inorganic fractions contributed similar amounts towards total dissolved nitrogen from the two pasture catchments; 47% and 53% for conservatively grazed pasture and 53% and 47% for heavily grazed pasture, respectively. Although there was limited data from brigalow scrub, estimations indicate a greater contribution of dissolved inorganic nitrogen (66%) than dissolved organic nitrogen (34%) towards total dissolved nitrogen. Oxidised nitrogen was the greatest fraction of dissolved inorganic nitrogen from all catchments; 99% for brigalow scrub, 94% for conservatively grazed pasture and 88% for heavily grazed pasture. The mean annual EMC for dissolved organic nitrogen was 1.3 mg/L from conservatively grazed pasture and 0.7 mg/L from heavily grazed pasture; and dissolved inorganic nitrogen was 1.8 mg/L and 0.6 mg/L, respectively.

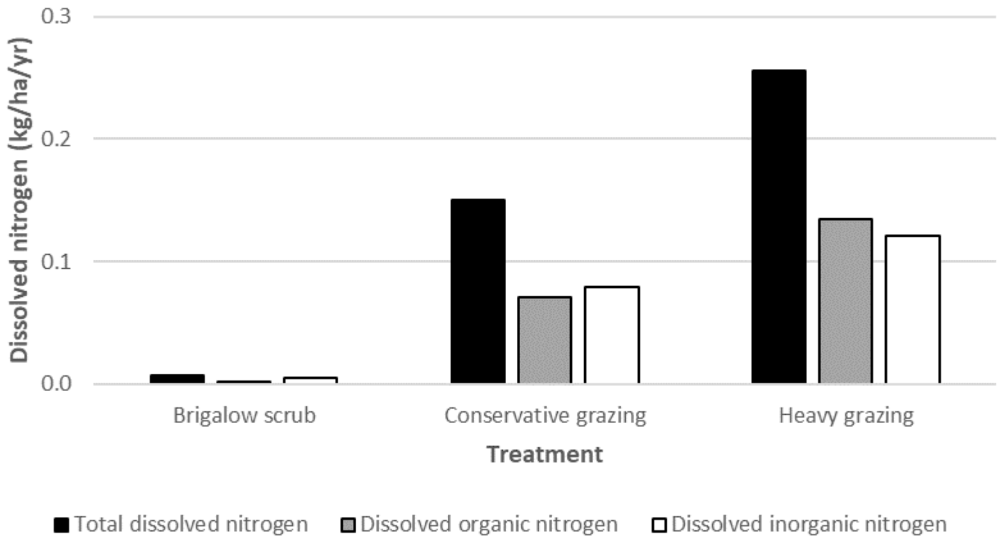

Figure 7: Mean annual load of dissolved nitrogen fractions in runoff from 2015 to 2018.

3.2.3 Phosphorus

Mean annual load of total phosphorus from the heavily grazed pasture was 2.6 times greater than from conservatively grazed pasture (Figure 8). Total phosphorus was composed of similar amounts of particulate and total dissolved phosphorus irrespective of grazing pressure; 59% and 41% for conservatively grazed pasture and 43% and 57% for heavily grazed pasture, respectively. Although there was limited data from brigalow scrub, estimations indicate a greater contribution of particulate phosphorus (72%) than total dissolved phosphorus (28%) towards total phosphorus. The dominant pathway of phosphorus loss was in a particulate form from brigalow scrub, but was unclear for the two pastures (Table 10). The mean annual EMC for total phosphorus was 0.81 mg/L from conservatively grazed pasture and 0.49 mg/L from heavily grazed pasture; particulate phosphorus was 0.50 mg/L and 0.22 mg/L; and total dissolved phosphorus was 0.31 mg/L and 0.27 mg/L, respectively.

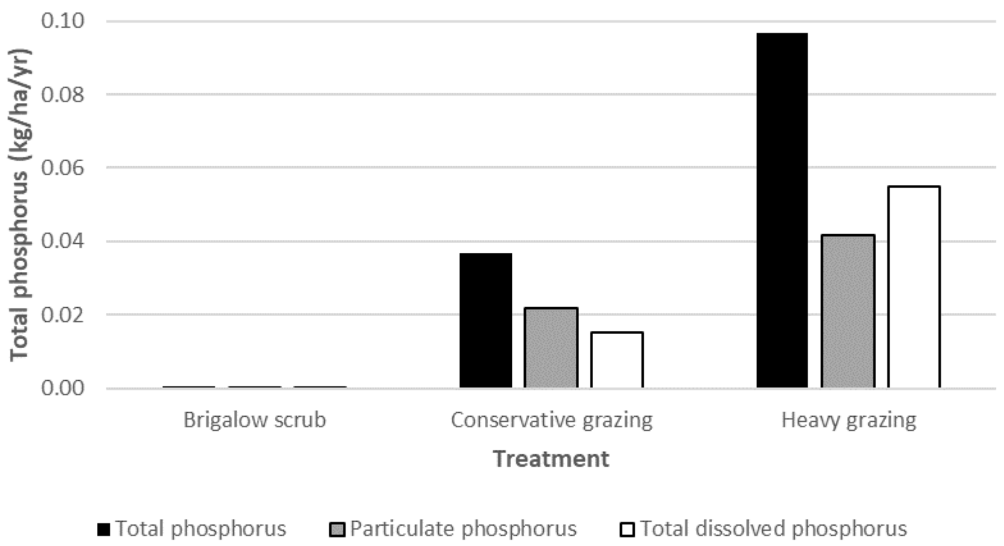

Figure 8: Mean annual load of total, particulate and dissolved phosphorus in runoff from 2015 to 2018.

Table 10: Dominant pathway of phosphorus loss in runoff from 2015 to 2018.

Year	Brigalow scrub	Conservative grazing	Heavy grazing
2015	Particulate	Particulate	No dominant
2016	No runoff	No dominant	Dissolved
2017	No runoff	No runoff	No runoff
2018	Particulate	No dominant	Particulate

Mean annual load of total dissolved phosphorus from the heavily grazed pasture was 3.6 times greater than from conservatively grazed pasture (Figure 9). Dissolved inorganic phosphorus was the greatest fraction of total dissolved phosphorus from all catchments; 78% from brigalow scrub, 84% from conservatively grazed pasture and 86% from heavily grazed pasture. The mean annual EMC for dissolved inorganic phosphorus was 0.26 mg/L from conservatively grazed pasture and 0.23 mg/L from heavily grazed pasture; and dissolved organic phosphorus was 0.05 mg/L and 0.04 mg/L, respectively.

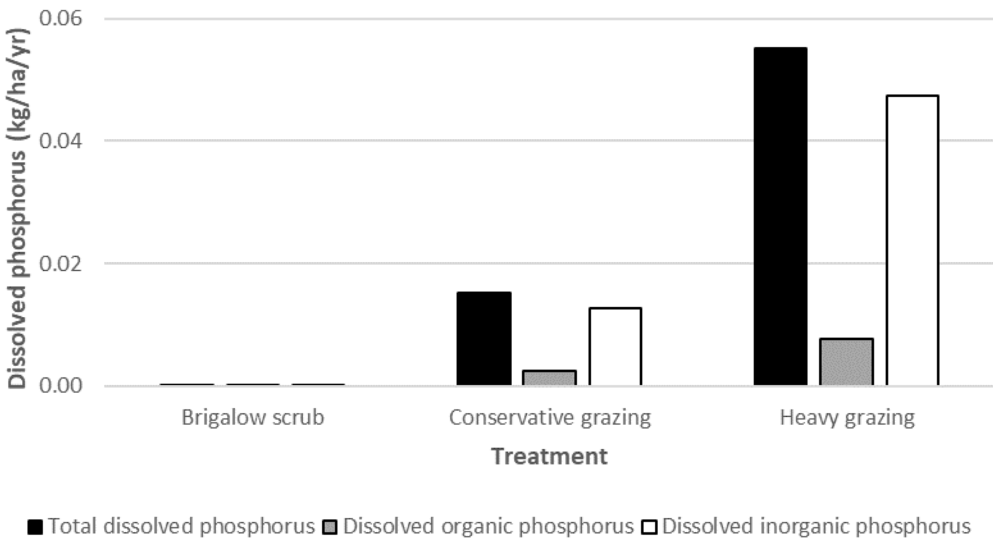

Figure 9: Mean annual load of dissolved phosphorus fractions in runoff from 2015 to 2018.

3.3 Ground Cover

In the two years prior to the commencement of this study, the two pastures were extensively spelled with less than nine weeks of grazing at conservative stocking rates. During this time, the effect of season on cover can be observed with both pastures having higher proportions of bare ground in the late dry season (Figure 10). At the commencement of this study in October 2014, the proportion of bare ground was similar in the conservatively (12.3%) and heavily grazed pastures (13.4%). At this time, 95% of the conservatively grazed pasture had cover levels of 78% or higher and 95% of the heavily grazed pasture had similar cover levels of 73% or higher. In April 2018, the amount of bare ground in the heavily grazed pasture (14.9%) was 2.5 times greater than in the conservatively grazed pasture (5.9%). Ground cover in the conservatively grazed pasture remained relatively constant during the study with 95% of the pasture having cover levels of 84% or higher in April 2018. However, cover levels across 95% of the heavily grazed pasture decreased to 57% or higher by January 2018 before increasing to 76% or higher in April 2018, similar to the distribution of cover at the commencement of the study. This analysis showed that the conservatively and heavily grazed pastures started in a similar condition, but an increase in bare ground and a corresponding decrease in ground cover were observed over time in the heavily grazed pasture.

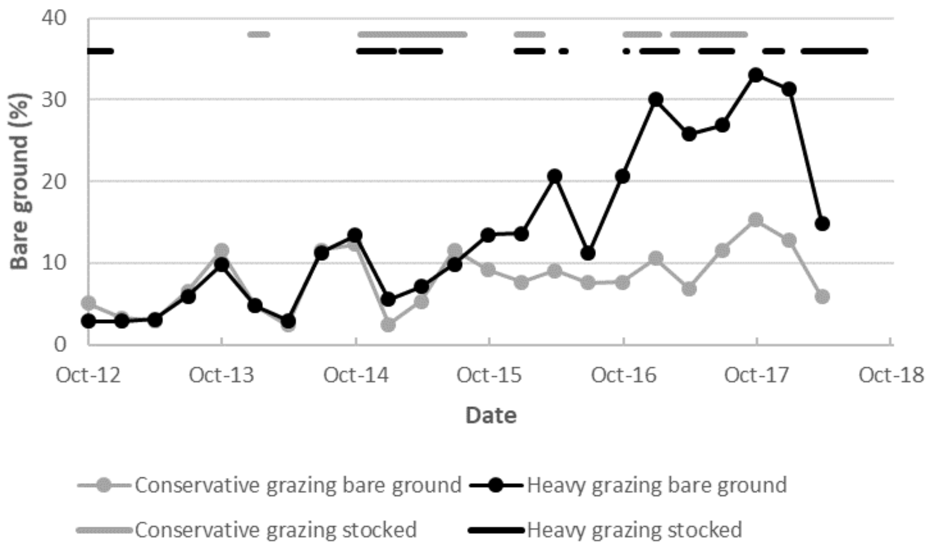

Figure 10: Measurements of bare ground in the two pastures related to cattle stocking.

3.4 Pasture Biomass

Overall, the heavily grazed catchment had lower pasture biomass than the conservatively grazed catchment (Figure 11). In the 2014 late wet season, prior to the commencement of the study, there was similar biomass in both the conservatively (6.9 t/ha) and heavily grazed pastures (6.2 t/ha). Biomass in the 2015 late wet season had increased 2.7 t/ha in the conservatively grazed pasture (9.6 t/ha) with little change in the heavily grazed pasture (6.5 t/ha). Biomass in the heavily grazed pasture went from 90% of the biomass in the conservatively grazed pasture in 2014 to 68% in 2015.

In the 2016 late wet season, biomass had reduced 53% under conservative grazing (4.5 t/ha) and 57% under heavy grazing (2.8 t/ha) compared to the previous year (Figure 11). The difference in biomass between the two pastures was 63%, similar to the previous year. Biomass continued to decline in both pastures over the next six months, with a 43% reduction in the conservatively grazed pasture to 2.5 t/ha and a much greater 83% reduction in the heavily grazed pasture to 0.5 t/ha. Biomass in the heavily grazed pasture during the 2016 late dry season was reduced to 19% of that from the conservatively grazed pasture.

In the 2017 late dry season, biomass had increased to 5.0 t/ha under conservative grazing and 3.1 t/ha under heavy grazing (Figure 11). Pasture biomass in the heavily grazed catchment increased to 62% of that from the conservatively grazed catchment, similar to the 2015 and 2016 late wet seasons. In the 2018 late dry season, biomass had increased 5% under conservative grazing (5.3 t/ha) whereas biomass under heavy grazing (0.4 t/ha) had declined 86% compared to the previous year. Biomass in the heavily grazed pasture during the 2018 late dry season was reduced to 8% of that from the conservatively grazed pasture.

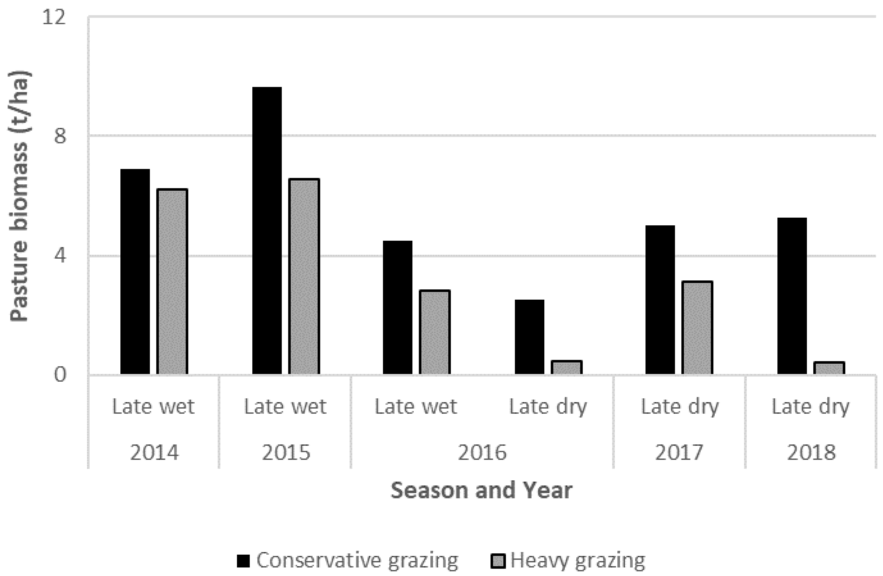

Figure 11: Pasture biomass in the two pastures from 2015 to 2018.

3.5 Qualitative Pasture Assessment

Table 11 provides a visual comparison of the conservatively and heavily grazed pastures during the late wet and late dry seasons over the 2015 to 2018 hydrological years. These photographs show lower ground cover and pasture biomass from the heavily grazed pasture compared to the conservatively grazed pasture. Table 12 provides a visual comparison of the two BCS pastures with five other grazed properties under different ownership in the Fitzroy Basin. The five properties appear to have lower ground cover and pasture biomass than the heavily grazed pasture.

Table 11: Photographic comparison of ground cover and pasture biomass from the two pastures in the late wet and late dry seasons from 2015 to 2018.

Year	Late wet season		Late dry season	
	Conservative grazing	Heavy grazing	Conservative grazing	Heavy grazing
2015			No photo	No photo
2016				
2017				
2018				

Table 12: Photographic comparison of the two Brigalow Catchment Study pastures compared to five other heavily grazed properties within the Fitzroy Basin during the 2018 late dry season.

Site and grazing pressure	Landscape	Ground Cover
Brigalow Catchment Study Conservative grazing		
Brigalow Catchment Study Heavy grazing		
Property 1 Fitzroy Basin Heavy grazing		
Property 2 Fitzroy Basin Heavy grazing		
Property 3 Fitzroy Basin Heavy grazing		
Property 4 Fitzroy Basin Heavy grazing		
Property 5 Fitzroy Basin Heavy grazing		

4 Discussion

4.1 Effect of Grazing Pressure on Hydrology

Changing land use from virgin brigalow scrub to conservatively grazed pasture at the long-term BCS has doubled total runoff (Thornton *et al.* 2007) and increased average and maximum peak runoff rates by 1.5 times and 3 times, respectively, when runoff occurred from both catchments (Thornton and Yu 2016). Over the four below average rainfall years of this study, heavy grazing of rundown pasture at stocking rates recommended for newly established pasture resulted in 3.6 times more total runoff and 3.3 times greater average peak runoff rate than the conservatively grazed pasture. At the end of the four year study, the heavily grazed pasture had 2.5 times more bare ground and only 8% of the pasture biomass compared to the conservatively grazed pasture. In years when no runoff occurred from brigalow scrub, total runoff from the conservatively grazed pasture was an absolute anthropogenic increase attributable to land use change. Runoff is known to increase with a decline in ground cover and/or biomass (Bartley *et al.* 2010; McIvor *et al.* 1995; Silburn *et al.* 2011), so an increase in runoff from the heavily grazed catchment was expected. This reflects numerous other studies that have reported greater runoff from grazed than ungrazed areas and/or pastures with higher stocking rates (Duniway *et al.* 2018; Filet and Osten 1996; Mapfumo *et al.* 2002; O'Reagain 2011; Silcock *et al.* 2005; van Oudenhoven *et al.* 2015).

Ground cover is an easily measured and visually evident indicator of land condition. While increases in runoff are commonly attributed to or observed in partnership with declining ground cover, the landscape response is more complex. For example, Thornton *et al*. (2007) showed that changed water use patterns was the primary driver of increased runoff when native vegetation was replaced with improved grass pasture, and that increased compaction and reduced ground cover, soil structure and infiltration rate were secondary drivers. Increased runoff, and subsequently increased loads of nutrients in runoff, are effectively a reduction in plant available water capacity and fertility of soils which leads to reduced pasture growth.

Persistent heavy grazing also changes the species composition of pasture over time leading to a decline in desirable (perennial, palatable and productive) species and an increase in less desirable (annual, unpalatable and less productive) species. For example, studies in the Burdekin Basin have attributed the transition of productive native grass species, such as black speargrass (*Heteropogon contortus*) and desert bluegrass (*Bothriochloa ewartiana*), to the less productive and less drought tolerant Indian couch (*Bothriochloa pertusa*) to a combination of drought and heavy grazing (Bartley *et al.* 2014; Spiegel 2016). Therefore, runoff, plant available water capacity, pasture growth and changes in pasture species composition are all intrinsically linked by the management of grazing pressure.

Intervention to break the cycle of declining land condition can be achieved with the adoption of improved management practices; however, the time required to restore healthy eco-hydrological function may vary from years to decades (Bartley *et al.* 2014; Hawdon *et al.* 2008; Roth 2004; Silcock *et al.* 2005). For example, a landholder in the Burdekin Basin reported improved land condition with the adoption of a safe long-term carrying capacity and pasture spelling (Landsberg *et al.* 1998). The property had reduced income during the three year transition phase; however, it became profitable with less cattle once the perennial grasses recovered. Other research in the Burdekin Basin clearly indicates that sustainable grazing management is profitable over extended time periods and varying climatic cycles (O'Reagain *et al.* 2011). Nonetheless, from both an environmental and economic perspective, it is better to improve grazing management before a dramatic decline in land condition occurs.

4.2 Effect of Grazing Pressure on Water Quality

Heavily grazed pasture had higher loads and lower EMCs for all water quality parameters compared to conservatively grazed pasture. In years when no runoff occurred from brigalow scrub, total runoff and subsequent loads of total suspended solids and nutrients from the conservatively grazed pasture were an absolute anthropogenic increase attributable to land use change. Over four below average rainfall years, this study typically had lower loads and higher EMCs than previously reported for the BCS during wetter periods and over longer timeframes (Elledge and Thornton 2017; Thornton and Elledge 2013; Thornton and Elledge 2014). These trends indicate that increased flow, whether from above average rainfall or a treatment (grazing pressure) effect, results in dilution of total suspended solids and nutrients leading to lower EMCs. However, the dilution effect was not strong enough to result in reduced loads. Dilution effects have been reported for sediment and nutrient concentrations within events (Schepers and Francis 1982), within seasons (Hay *et al.* 2006; Schepers *et al.* 1982), in the transition from dry to wet seasons (Vink *et al.* 2007), and also on an annual basis over multiple years (Bartley *et al.* 2014; Miller *et al.* 2017). This study reflects other publications that have reported increased loads with increased flow (Hay *et al.* 2006; Schepers *et al.* 1982).

4.2.1 Total Suspended Solids

Runoff from heavily grazed pasture had 3.2 times more total suspended solids load than the conservatively grazed pasture. An increase in suspended solids with a decrease in ground cover is the same as the trend observed between runoff and cover in this study, which is a relationship often cited in the literature (Bartley *et al.* 2010; McIvor *et al.* 1995; Silburn *et al.* 2011). VegMachine® analysis showed decreased ground cover with increased grazing pressure. Despite similar cover levels in the two pastures initially, there was 2.5 times more bare ground in the heavily grazed pasture after four years compared to the conservatively grazed pasture. Mean annual loads for both the conservatively (14 kg/ha/yr) and heavily grazed pastures (46 kg/ha/yr) during the four below average rainfall years of this study were considerably lower than observed from the conservatively grazed pasture during an extremely wet period from 2010 to 2012, a return to average conditions from 2013 to 2014, and also modelled loads for the period 1984 to 2010 (Elledge and Thornton 2017; Thornton and Elledge 2013; Thornton and Elledge 2014). Mean annual load from these three periods was 258 kg/ha/yr (range 20 to 468 kg/ha/yr). Loads from this study were also lower than more erosive landscapes with shallower soils elsewhere in the Fitzroy Basin (Silburn *et al.* 2011) and in the nearby Burdekin Basin (Bartley *et al.* 2014; Hawdon *et al.* 2008).

Mean annual EMCs of total suspended solids from both the conservatively (278 mg/L) and heavily grazed pastures (235 mg/L) were similar to those previously reported for the conservatively grazed pasture during wetter periods and over longer timeframes (301 mg/L; range 95 to 916 mg/L) (Elledge and Thornton 2017; Thornton and Elledge 2013; Thornton and Elledge 2014). These values also fit within the ranges reported for grazing on both improved and native pastures dominated (>90%) by a single land use (Bartley *et al.* 2012). Bartley *et al*. (2012) reviewed water quality data from across Australia and found that EMCs of total suspended solids were lower from forests than improved pasture, and both these land uses were lower than from native pastures. In contrast, EMCs from brigalow scrub of the BCS were generally higher than from conservatively grazed pasture when runoff occurred from both catchments (Elledge and Thornton 2017; Thornton and Elledge 2013; Thornton and Elledge 2014). This highlights the importance that hydrological characteristics, vegetation type and landscape condition (i.e. ground cover) have on the resulting total suspended solids loads and concentrations. Data from the BCS is able to fill the knowledge gap of water quality from brigalow lands in the Fitzroy Basin, which can further refine estimations of the impact of grazing land management on Great Barrier Reef water quality.

4.2.2 Nitrogen

Similar total suspended solids, loads of all nitrogen parameters during the four below average rainfall years were greater from heavily than conservatively grazed pasture while EMCs were lower from heavily grazed pasture. This reflects other studies that have reported greater nitrogen loads from grazed than ungrazed areas and also from heavier than lighter grazing pressures (Daniel *et al.* 2006; Park *et al.* 2017). Mean annual loads of total nitrogen (0.29 kg/ha/yr) and dissolved inorganic nitrogen (0.08 kg/ha/yr) from the conservatively grazed pasture in this study were lower than previously reported during wetter periods and over longer timeframes; 2.6 kg/ha/yr (range 0.6 to 5.1 kg/ha/yr) and 0.37 kg/ha/yr (range 0.06 to 0.81 kg/ha/yr), respectively (Elledge and Thornton 2017; Thornton and Elledge 2013; Thornton and Elledge 2014).

In contrast, EMCs of total nitrogen (6.49 mg/L) and dissolved inorganic nitrogen (1.81 mg/L) from the conservatively grazed pasture in this study were higher than previously reported; 2.4 mg/L (range 2.0 to 3.2 mg/L) and 0.41 mg/L (range 0.11 to 0.80 mg/L), respectively (Elledge and Thornton 2017; Thornton and Elledge 2013; Thornton and Elledge 2014). EMCs for these two nitrogen parameters were within the range for improved pastures in Australia, but exceeded the range for native pastures when the majority of the upstream area was under a single land use (Bartley *et al.* 2012). However, under the more rigorous criteria of upstream area dominated (>90%) by a single land use, the total nitrogen EMC in this study exceeded the ranges for both improved and native pastures. Comparable data was not available for dissolved inorganic nitrogen.

These high EMCs are likely a reflection of the high soil fertility of brigalow lands compared to the rangeland, savannah and woodland landscapes from which comparable data was available. This is supported by long-term total nitrogen (14.4 mg/L; range 9.9 to 20.2 mg/L) and dissolved inorganic nitrogen (4.82 mg/L; range 1.94 to 7.01 mg/L) EMCs from brigalow scrub (Elledge and Thornton 2017; Thornton and Elledge 2013; Thornton and Elledge 2014) which greatly exceed the ranges given for forest in Bartley *et al.* (2012). Furthermore, modelling of long-term water quality indicates that brigalow scrub has higher loads and concentrations of nitrogen (total and dissolved) compared to conservatively grazed pasture (Elledge and Thornton 2017). This is in contrast to a number of Australian and international studies that have noted higher loads of nitrogen from pasture than forest (Quinn and Stroud 2002; Udawatta *et al.* 2011; Vink *et al.* 2007). This highlights the uniqueness of brigalow lands where nitrogen fixation by brigalow (*Acacia harpophylla*) leads to high soil fertility, and hence higher losses of nitrogen in runoff, compared to other landscapes (Thornton and Elledge 2018; Webb *et al.* 1982; Yule 1989).

The limited data collected during this study showed that nitrogen lost in runoff from brigalow scrub was predominately in the dissolved phase. This phase was dominated by dissolved inorganic nitrogen which in turn was dominated by oxidised nitrogen. In contrast, nitrogen from the two pastures was lost in both particulate and dissolved phases. Both dissolved organic and inorganic nitrogen made substantial contributions to the dissolved phase. Oxidised nitrogen dominated the dissolved inorganic nitrogen fraction. This reflects numerous authors that have highlighted the importance of dissolved organic nitrogen when considering nitrogen losses (Alfaro *et al.* 2008; Robertson and Nash 2008; Van Kessel *et al.* 2009). This is certainly the case for grazed landscapes, as dissolved organic nitrogen is known to increase with the application of cattle urine and dung (Van Kessel *et al.* 2009; Wachendorf *et al.* 2005), and concentrations have also been shown to increase with increased grazing pressure (Owens *et al.* 1989).

4.2.3 Phosphorus

Similar to total suspended solids and nitrogen, loads of all phosphorus parameters during the four below average rainfall years were greater from heavily than conservatively grazed pastures while EMCs were lower from heavily grazed pastures. This reflects other studies that have reported greater phosphorus loads from grazed than ungrazed areas and also from heavier than lighter grazing pressures (Butler *et al.* 2008; Daniel *et al.* 2006; Park *et al.* 2017; Vink *et al.* 2007). Mean annual loads of total phosphorus (0.04 kg/ha/yr) and dissolved inorganic phosphorus (0.01 kg/ha/yr) from the conservatively grazed pasture in this study were lower than previously reported during wetter periods and over longer timeframes; 0.38 kg/ha/yr (range 0.07 to 0.76 kg/ha/yr) and 0.20 kg/ha/yr (range 0.04 to 0.42 kg/ha/yr), respectively (Elledge and Thornton 2017; Thornton and Elledge 2013; Thornton and Elledge 2014).

In contrast, EMCs of total phosphorus (0.81 mg/L) and dissolved inorganic phosphorus (0.26 mg/L) from the conservatively grazed pasture were higher than previously reported; 0.32 mg/L (range 0.23 to 0.41 mg/L) and 0.17 mg/L (range 0.10 to 0.22 mg/L), respectively (Elledge and Thornton 2017; Thornton and Elledge 2013; Thornton and Elledge 2014). The total phosphorus EMC fits within the range for both improved and native pastures within Australia (Bartley *et al.* 2012). Although the EMC for dissolved inorganic phosphorus was just above the range for improved pastures, it greatly exceeded the range for native pastures (Bartley *et al.* 2012). Similarly, the EMC for dissolved organic phosphorus in this study (0.05 mg/L) greatly exceeded both the improved and native pasture ranges of Bartley *et al*. (2012).

Similar to the response for nitrogen, these high EMCs are likely a reflection of the high soil fertility of brigalow lands. This is supported by long-term EMCs of total phosphorus (0.79 mg/L; range 0.32 to 2.19 mg/L) and dissolved inorganic phosphorus (0.16 mg/L; range 0.10 to 0.29 mg/L) from brigalow scrub (Elledge and Thornton 2017; Thornton and Elledge 2013; Thornton and Elledge 2014) which greatly exceed the ranges given for forest in Bartley *et al.* (2012). Furthermore, soil phosphorus levels prior to land development at the BCS were considered moderate (13.7 mg/kg; range 13.3 to 14.0 mg/kg) based on the classification of Ahern *et al*. (1994). Levels increased rapidly becoming high to very high (34.7 mg/kg; range 24 to 44 mg/kg) following clearing and burning due to the resulting ash bed. However, soil phosphorus levels under grazing then declined back to a moderate level (12.6 mg/kg; range 11.0 to 14.6 mg/kg) over the next 32 years (unpublished BCS data). This is in stark contrast to the low, deficient (very low) and acute (extremely low) status of soil phosphorus given to 72% of the central and north-east Queensland grazing lands (Ahern *et al.* 1994) and the deficient and acute status given to 68% of northern Australian soils (McCosker and Winks 1994).

Phosphorus loss from uncultivated fields and grazed pasture is typically in the dissolved phase, which is dominated by dissolved inorganic phosphorus (Alfaro *et al.* 2008; Gillingham and Gray 2006; Potter *et al.* 2006; Robertson and Nash 2008). The limited data collected during this study showed that phosphorus loss from brigalow scrub may be dominated by particulate phosphorus while the grass pastures lost phosphorus in both particulate and dissolved phases. Higher EMCs of dissolved inorganic phosphorus from conservatively grazed pasture compared to brigalow scrub has previously been attributed to the presence of grazing animals and their dung (Elledge and Thornton 2017), which is in agreement with the literature (Schepers *et al.* 1982; Vadas *et al.* 2011).

4.3 Stocking Rates and Safe Long-Term Carrying Capacity

Published stocking rates for buffel grass pastures on brigalow lands vary from 2 ha/head to 10 ha/head (Graham *et al.* 1991; Lawrence and French 1992; Noble *et al.* 2000; Partridge *et al.* 1994; Paton *et al.* 2011; Peck *et al.* 2011). Some authors acknowledge that stocking rates should be adjusted for landscape and seasonal variability (Graham *et al.* 1991; Lawrence and French 1992; Paton *et al.* 2011), while others note that stocking rates should be reduced over time as pasture productivity declines (Noble *et al.* 2000; Partridge *et al.* 1994; Peck *et al.* 2011). For example, Noble *et al*. (2000) recommends 2 ha/head on newly established buffel grass pastures and 3 ha/head on rundown buffel grass pastures. Daily live weight gains of 0.5 kg/head are considered possible from newly established pastures (Lawrence and French 1992; Radford *et al.* 2007); however, stocking rates should be adjusted to achieve daily weight gains of 0.4 kg/head on rundown pastures (Partridge *et al.* 1994).

In line with these recommendations and to maintain industry relevance, the average stocking rate of the conservatively grazed pasture during this study was 0.17 AE/ha/yr, which equates to 5.9 ha/AE. Historically, stocking rates for this pasture were 2.2 ha/AE on newly established buffel grass pasture when the study commenced, and decreased to 3.8 ha/AE over the next 21 years (Radford *et al.* 2007). The average long-term (1984 to 2017) stocking rate was 3.3 ha/AE (unpublished BCS data). Daily weight gains in the order of 0.5 kg/head were achieved initially and have been obtained periodically since (Radford *et al.* 2007; Thornton and Buck 2011); however, maintaining the 2.2 ha/AE stocking rate during the first 11 years following pasture establishment saw daily weight gains decline to about 0.3 kg/head (Radford *et al.* 2007).

The average stocking rate in the heavily grazed pasture was 0.54 ha/AE/yr, which equates to 1.9 ha/AE. Despite the age of the pasture (40 to 50 years old), this stocking rate was similar to recommended stocking rates for newly established buffel grass pastures. Given the difficulties encountered in changing the traditional paradigm of “more cattle means more money” towards lighter stocking rates despite equal or greater economic return (Moravek *et al.* 2017; O'Reagain *et al.* 2011; Stockwell *et al.* 1991), it is likely that high stocking rates are still used within the industry. This is supported by the qualitative pasture assessment in this study which shows better management of the heavily grazed pasture of the BCS compared to five properties in the Fitzroy Basin. Thus, ground cover, pasture biomass, hydrology and water quality data for the heavily grazed pasture in this report may still be an underestimate for some properties.

The concept of safe long-term carrying capacity for sustainable grazing management benefits productivity, land condition and runoff water quality by balancing pasture utilisation with pasture growth (O’Reagain *et al.* 2014). A utilisation rate between 15 and 30% of pasture growth has been considered a safe long-term carrying capacity (O'Reagain *et al.* 2011; Peck *et al.* 2011). Safe long-term carrying capacity can be calculated using pasture biomass, dietary intake requirements of cattle and pasture utilisation rates. For the conservatively grazed pasture, a safe long-term carrying capacity was 3.4 ha/AE based on long-term pasture biomass of 3,500 kg/ha (Radford *et al.* 2007), an estimated dietary intake of 2.2% bodyweight per day (Minson and McDonald 1987) and a high but still economically viable utilisation rate of 30% (Bowen and Chudleigh 2017). Although a safe long-term carrying capacity can be calculated for a specific location, stocking rates should be adjusted annually at the end of the summer growing period to account for pasture biomass (Lawrence and French 1992).

4.4 *Implications for the Grazing Industry*

Long-term data from the BCS suggests that a stocking rate of 3.4 ha/AE is a safe long-term carrying capacity for rundown (30 to 40 years old) buffel grass pasture established on predominantly clay soils previously dominated by brigalow scrub. This recommendation is based on long-term pasture biomass and cattle live weight gains from the study site, and stocking rates may need to be reduced at other locations unable to produce similar amounts of pasture biomass (average 3,500 kg/ha). Failure to reduce stocking rates on rundown pastures to match safe long-term carrying capacity led to increased runoff, and subsequently increased loads of total suspended solids, nitrogen and phosphorus in runoff. While limited water quality data was collected during the four below average rainfall years of this study, total nitrogen and phosphorus loads both had substantial contributions of particulate and dissolved fractions. Although heavily grazed pasture had the highest runoff and greatest loads of all total suspended solids and nutrient parameters, it had the lowest EMCs. This indicates that total runoff and peak runoff rate were key drivers of runoff loads. Heavy grazing pressure reduced ground cover which demonstrates the value of ground cover as an indicator of degraded land condition. This study compliments other research that has reported improved land condition and reduced economic risk by transitioning from heavy to conservative grazing pressures. This demonstrates that reducing grazing pressure is a realistic option for landholders that will also have benefits for runoff water quality.

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Appendix 1: EMC Method Comparison

Introduction

The traditional method for calculating an event mean concentration (EMC) is total load for all years divided by total flow for all years. However, this method can be confounded by both the time step of the input data (i.e. daily, monthly, yearly or event based) and the need to develop a mean or representative EMC from multiple time steps, events and/or sites. To overcome these issues, the Brigalow Catchment Study (BCS) has historically calculated a mean EMC as the arithmetic mean of all annual EMCs, where each annual EMC was calculated as the arithmetic mean of all event based EMCs in a year. Comments received during the Paddock to Reef independent review in October 2015 indicated that this method may be mathematically invalid, and similar comments were reiterated to authors during the review process for Elledge and Thornton (2017). A validation of the applicability of this method was required, as EMC data from the BCS has been used in APSIM, HowLeaky? and Source Catchments modelling which all underpin the Paddock to Reef Program.

Method

A comparison of methods for calculating a mean EMC was undertaken using 16 years of water quality data from the five catchments of the BCS (Figure A1). This data was collected from 2000 to 2015 during parts of the land use comparison (Stage III) and adaptive land management (Stage IV) phases. Table 1 in Section 2.2 shows the land use in these catchments. Note data in this appendix uses different catchments and time periods compared to the rest of the report. Further details on these catchments are provided in other documents (Cowie *et al.* 2007; Elledge and Thornton 2017; Radford *et al.* 2007; Thornton *et al.* 2007; Thornton and Elledge 2013).

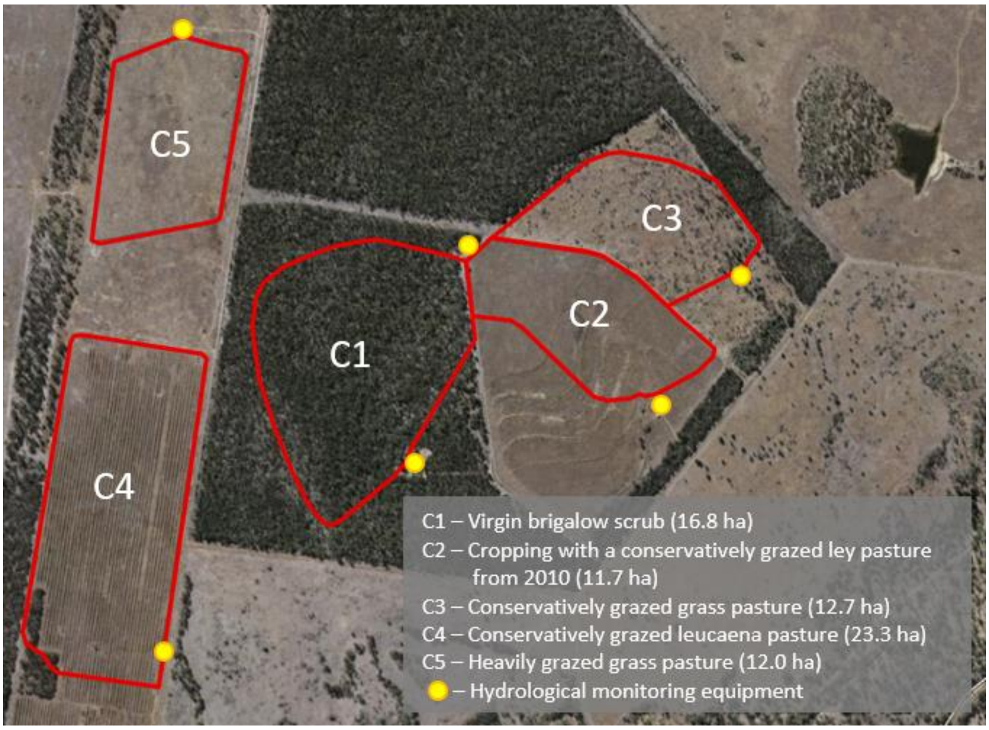

Figure A1: Aerial photo of the Brigalow Catchment Study showing the hydrological (runoff) boundaries and location of monitoring equipment within the five catchments.

All available water quality data from the five catchment was used, including total and dissolved fractions of solids, nitrogen, phosphorus and carbon. Four methods were used to calculate a mean EMC:

(1) Total load for all years divided by total flow for all years (traditional method);
(2) Arithmetic mean of all event based EMCs, where each EMC was calculated as total load for an event divided by total flow for an event;
(3) Arithmetic mean of all annual EMCs, where each annual EMC was calculated as the arithmetic mean of all event based EMCs in a year (historically used for BCS data including the water quality results in this report);
(4) Arithmetic mean of all annual mean concentrations (AMCs), where each AMC was calculated as total load in a year divided by total flow in a year.

The EMCs for Methods 2 to 4 were plotted against the EMC for Method 1, and a regression analysis was performed to determine their correlation.

Results and Discussion

Three alternative methods for calculating a mean EMC were compared to the traditional method (Figure A2). Regression analyses showed that between 95% and 97% of the variability can be explained by the linear models, indicating that all four methods are equally valid. The BCS will continue to use the arithmetic mean of all annual EMCs to calculate a long-term EMC.

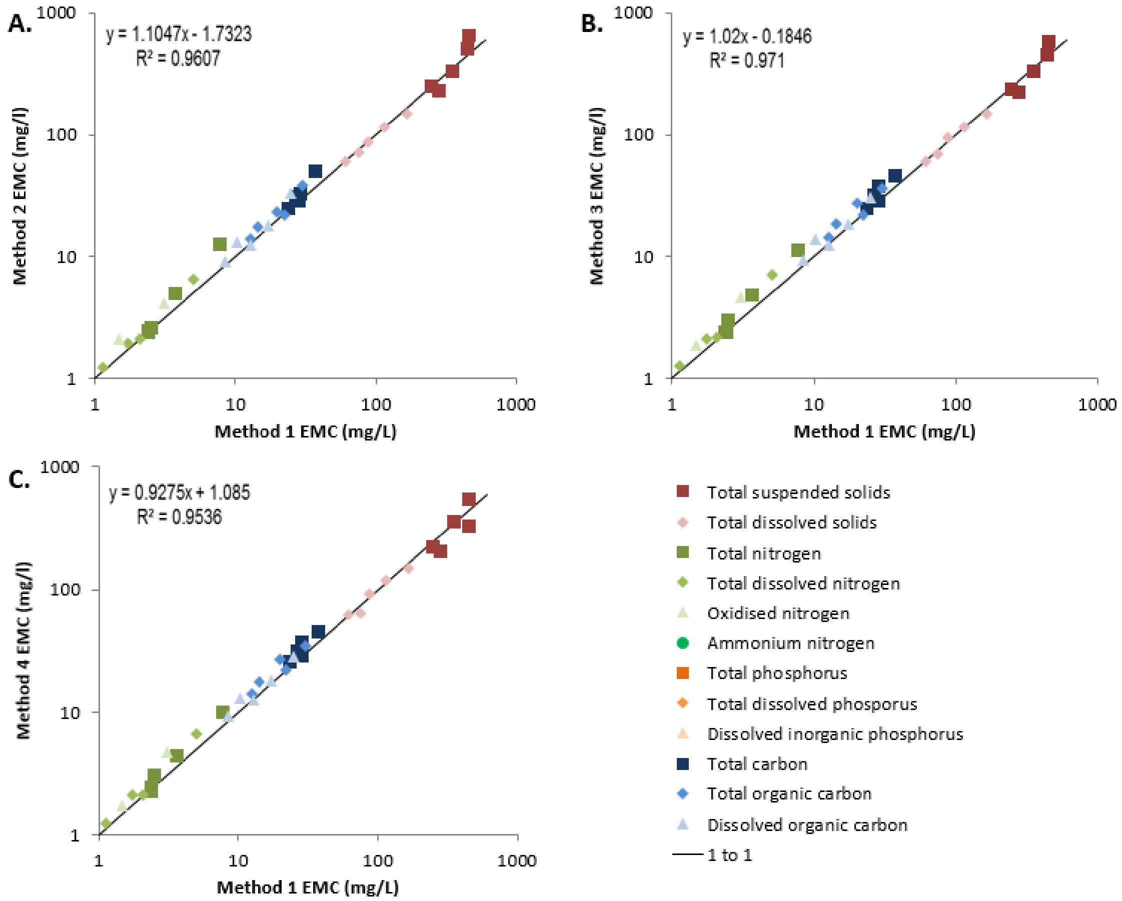

Figure A2: Three alternative methods for calculating an event mean concentration (EMC) compared to the traditional method (Method 1) using 16 years of water quality data from the Brigalow Catchment Study. Note that not all parameters are visible due to overlaying data points and very low values.

Appendix 2: Tabulated Annual Loads and EMCs

Table A1: 2015 hydrological year loads and event mean concentrations (EMCs) for total suspended solids, nitrogen and phosphorus in runoff.

	Parameter	Brigalow scrub	Conservative grazing	Heavy grazing
TSS	Total load (kg/ha/yr)	1	20	101
	Mean EMC (mg/L)	No data	99	321
TN	Total load (kg/ha/yr)	0.03	0.70	0.69
	Mean EMC (mg/L)	No data	7.06	2.37
PN	Total load (kg/ha/yr)	0.01	0.36	0.40
	Mean EMC (mg/L)	No data	4.03	1.39
TDN	Total load (kg/ha/yr)	0.02	0.35	0.28
	Mean EMC (mg/L)	No data	3.03	0.98
DON	Total load (kg/ha/yr)	0.01	0.18	0.20
	Mean EMC (mg/L)	No data	1.25	0.69
DIN	Total load (kg/ha/yr)	0.01	0.17	0.08
	Mean EMC (mg/L)	No data	1.78	0.29
TP	Total load (kg/ha/yr)	<0.01	0.10	0.17
	Mean EMC (mg/L)	No data	1.00	0.58
PP	Total load (kg/ha/yr)	<0.01	0.06	0.09
	Mean EMC (mg/L)	No data	0.68	0.31
TDP	Total load (kg/ha/yr)	<0.01	0.04	0.08
	Mean EMC (mg/L)	No data	0.32	0.28
DOP	Total load (kg/ha/yr)	<0.01	0.01	0.01
	Mean EMC (mg/L)	No data	0.05	0.04
DIP	Total load (kg/ha/yr)	<0.01	0.03	0.07
	Mean EMC (mg/L)	No data	0.27	0.23

Table A2: 2016 hydrological year loads and event mean concentrations (EMCs) for total suspended solids, nitrogen and phosphorus in runoff.

	Parameter	Brigalow scrub	Conservative grazing	Heavy grazing
TSS	Total load (kg/ha/yr)	No runoff	36	36
	Mean EMC (mg/L)	No runoff	456	125
TN	Total load (kg/ha/yr)	No runoff	0.47	0.79
	Mean EMC (mg/L)	No runoff	5.92	2.80
PN	Total load (kg/ha/yr)	No runoff	0.22	0.17
	Mean EMC (mg/L)	No runoff	2.78	0.61
TDN	Total load (kg/ha/yr)	No runoff	0.25	0.62
	Mean EMC (mg/L)	No runoff	3.13	2.18
DON	Total load (kg/ha/yr)	No runoff	0.10	0.26
	Mean EMC (mg/L)	No runoff	1.30	0.92
DIN	Total load (kg/ha/yr)	No runoff	0.15	0.36
	Mean EMC (mg/L)	No runoff	1.83	1.26
TP	Total load (kg/ha/yr)	No runoff	0.05	0.14
	Mean EMC (mg/L)	No runoff	0.61	0.49
PP	Total load (kg/ha/yr)	No runoff	0.02	0.03
	Mean EMC (mg/L)	No runoff	0.32	0.11
TDP	Total load (kg/ha/yr)	No runoff	0.02	0.11
	Mean EMC (mg/L)	No runoff	0.30	0.38
DOP	Total load (kg/ha/yr)	No runoff	<0.01	0.01
	Mean EMC (mg/L)	No runoff	0.04	0.05
DIP	Total load (kg/ha/yr)	No runoff	0.02	0.10
	Mean EMC (mg/L)	No runoff	0.25	0.34

Table A3: 2018 hydrological year loads and event mean concentrations (EMCs) for total suspended solids, nitrogen and phosphorus in runoff.

	Parameter	Brigalow scrub	Conservative grazing	Heavy grazing
TSS	Total load (kg/ha/yr)	0.7	0.3	47
	Mean EMC (mg/L)	No data	No data	257
TN	Total load (kg/ha/yr)	0.02	<0.01	0.38
	Mean EMC (mg/L)	No data	No data	1.99
PN	Total load (kg/ha/yr)	0.01	<0.01	0.26
	Mean EMC (mg/L)	No data	No data	1.41
TDN	Total load (kg/ha/yr)	0.01	<0.01	0.12
	Mean EMC (mg/L)	No data	No data	0.58
DON	Total load (kg/ha/yr)	<0.01	<0.01	0.07
	Mean EMC (mg/L)	No data	No data	0.37
DIN	Total load (kg/ha/yr)	0.01	<0.01	0.05
	Mean EMC (mg/L)	No data	No data	0.21
TP	Total load (kg/ha/yr)	<0.01	<0.01	0.08
	Mean EMC (mg/L)	No data	No data	0.40
PP	Total load (kg/ha/yr)	<0.01	<0.01	0.05
	Mean EMC (mg/L)	No data	No data	0.26
TDP	Total load (kg/ha/yr)	<0.01	<0.01	0.03
	Mean EMC (mg/L)	No data	No data	0.15
DOP	Total load (kg/ha/yr)	<0.01	<0.01	<0.01
	Mean EMC (mg/L)	No data	No data	0.02
DIP	Total load (kg/ha/yr)	<0.01	<0.01	0.03
	Mean EMC (mg/L)	No data	No data	0.13

Appendix 3: Publications

Journal Papers

Three journal papers that used BCS data were published during the funded period:

(1) Elledge A. and Thornton C. (2017). Effect of changing land use from virgin brigalow (*Acacia harpophylla*) woodland to a crop or pasture system on sediment, nitrogen and phosphorus in runoff over 25 years in subtropical Australia. *Agriculture, Ecosystems and Environment* **239**, pp. 119-131.

(2) Thornton C. and Elledge A. (2016). Tebuthiuron movement via leaching and runoff from grazed Vertisol and Alfisol soils in the Brigalow Belt bioregion of central Queensland, Australia. *Journal of Agricultural and Food Chemistry* **64** (20), pp. 3949-3959.

(3) Thornton C. M. and Yu B. (2016). The Brigalow Catchment Study: IV. Clearing brigalow (*Acacia harpophylla*) for cropping or grazing increases peak runoff rate. *Soil Research* **54** (6), pp. 749-759.

Conference Papers and Presentations

Three seminars that used BCS data were presented at conferences during the funded period:

(1) Elledge A. E. and Thornton C. M. (2018). The Brigalow Catchment Study: The impacts of developing Acacia harpophylla woodland for cropping or grazing on hydrology, soil fertility and water quality in the Brigalow Belt bioregion of Australia. Natural resource science in action: Connecting people, science and purpose, Toowoomba.

(2) Thornton C., Elledge A., Shrestha K., Wallace S., Bosomworth B. and Yu B. (2017). The Brigalow Catchment Study: The impacts of developing Acacia harpophylla woodland for cropping or grazing on hydrology, soil fertility and water quality in the Brigalow Belt bioregion of Australia. International interdisciplinary conference on land use and water quality: Effect of agriculture on the environment, The Hague, Netherlands.

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Website

A portal for the BCS (www.brigalowcatchmentstudy.com) was developed during the funded period which provides access to rainfall and runoff data from all five monitored catchments, in addition to information on publications that have resulted from the long-term BCS.