Marine Pollution Bulletin 171 (2021) 112704

Contents lists available at ScienceDirect

Marine Pollution Bulletin

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

Heavy grazing of buffel grass pasture in the Brigalow Belt bioregion of Queensland, Australia, more than tripled runoff and exports of total suspended solids compared to conservative grazing

C.M. Thornton *, A.E. Elledge

Department of Resources, PO Box 1762, Rockhampton, Queensland 4700, Australia

ARTICLE INFO

Keywords:
Beef cattle
Brigalow Catchment Study
Ground cover
Land clearing
Land use change
VegMachine

ABSTRACT

Loss of sediment and particulate nutrients 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. This study measured differences in hydrology and water quality from conservative and heavy grazing pressures on rundown improved grass pastures in the Fitzroy Basin. Conservative grazing pressure was defined as the safe long-term carrying capacity for rundown buffel grass pasture, whereas heavy grazing pressure was defined as the recommended stocking rate for newly established buffel grass pasture. Heavy grazing of rundown pasture resulted in 2.5 times more bare ground and only 8% of the pasture biomass compared to conservative grazing. Heavy grazing also resulted in 3.6 times more total runoff and 3.3 times the peak runoff rate compared to conservative grazing. Loads of total suspended solids, nitrogen and phosphorus in runoff were also greater from heavy than conservative grazing.

1. Introduction

The Fitzroy Basin is Queensland's largest coastal catchment and is almost entirely contained within the Brigalow Belt bioregion of Australia. Both the basin and the wider bioregion have experienced some of the highest rates of land clearing in the world, with up to 93% of vegetation communities dominated by brigalow (*Acacia harpophylla*) cleared for agriculture since European settlement (Butler and Fairfax, 2003; Cogger et al., 2003; Tulloch et al., 2016). Grazing is the dominant land use in the Fitzroy Basin, with more than 2.6 million cattle over 11.1 Mha (Australian Bureau of Statistics, 2009; Meat and Livestock Australia, 2017a). 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, 2017a).

The 2017 Scientific Consensus Statement for Great Barrier Reef water quality identified the Fitzroy Basin as a high priority area for reducing fine sediment and particulate nutrients. This is due to their ongoing contribution to marine water quality decline and resultant damage to seagrass and coral reefs (Waterhouse et al., 2017). Increased adoption of best management practices for agriculture was identified as a key strategy to reduce sediment and nutrient loads in runoff. Within the Grazing Water Quality Risk Framework for 2017 to 2022, the lowest risk to water quality from hillslope pasture management is achieved by practices such as forage budgeting to determine carrying capacity, ground cover monitoring and the adoption of wet season spelling (The State of Queensland, 2020b). 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, light and heavy stocking rates were compared in the Burdekin Basin with 20 to 25% and 40 to 50% pasture utilisation, respectively (O'Reagain et al., 2008). A safe long-term carrying capacity is defined as the capacity of the pasture to sustainably carry livestock in the long-term whereas a safe pasture utilisation rate is defined as the proportion of annual forage growth that can be consumed by domestic livestock without adversely affecting land condition in the long-term (McKeon et al., 2009; Walsh and Cowley, 2011).

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). This reflects international literature from

* Corresponding author.
E-mail address: Craig.Thornton@resources.qld.gov.au (C.M. Thornton).

https://doi.org/10.1016/j.marpolbul.2021.112704
Received 6 January 2021; Received in revised form 13 June 2021; Accepted 4 July 2021
Available online 20 July 2021

at least the last 100 years that demonstrates heavy continuous grazing accelerates runoff and erosion (Hubbard et al., 2004). Multiple global meta-analyses have shown that grazing decreases ground cover and increases compaction, which consequently decreases protection from raindrop impact, aggregate stability and infiltration while increasing runoff. These impacts were greater from heavy grazing than conservative or rotational grazing (Byrnes et al., 2018; Eldridge et al., 2016; Lai and Kumar, 2020; McDonald et al., 2019; Sirimarco et al., 2018; Wang and Tang, 2019; Xu et al., 2018). Thus, erosion and sediment transport are primarily associated with high-density stocking and/or poor forage stands on grazed landscapes (Hubbard et al., 2004). Globally, degradation by overgrazing is estimated to effect 20 to 35% of permanent pastures, which total about half of the earths terrestrial surface (Byrnes et al., 2018; Lai and Kumar, 2020).

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). Managing grazing pressure is typically undertaken by varying stocking rate, as it is the most powerful management tool available to the grazier (Lawrence and French, 1992).

These interrelated land use and land management issues were a focus of the Reef 2050 Water Quality Improvement Plan (The State of Queensland, 2018). This plan seeks to improve Great Barrier Reef health and resilience by facilitating increased adoption of lower risk land management practices to achieve specific water quality targets. Progress towards these targets is measured via the Paddock to Reef Integrated Monitoring, Modelling and Reporting program (Paddock to Reef program) (Waterhouse et al., 2018). The Paddock to Reef program is underpinned by a modelling framework that ranges in scale from individual paddocks though to entire basins with real-world validation provided by numerous studies (Waterhouse et al., 2018). The Brigalow Catchment Study is a paddock scale study that is used to validate the effects of hillslope grazing management on water quality from the Fitzroy Basin. This long-term study has a paired catchment design where catchments are adjacent within a uniform landscape, whereas other paired catchment studies often have sites located further apart in the landscape which confounds interpretation due to inherent differences in soil, slope, vegetation and climatic sequences.

Despite the existence of about 200 paired catchment studies worldwide (Peel, 2009), only 13 of them are based in Australia and only three of these have any form of pasture treatment (Best et al., 2003). Two of the three pasture studies were based in Mediterranean climates (cool wet winters and hot dry summers) and are now both inactive (Best et al., 2003; Mein et al., 1988), whereas the third at the Brigalow Catchment Study was based in a semi-arid, subtropical climate (warm wet summers and cool dry winters) and remains active. Bartley et al. (2012) noted that there is a limited amount of Australian runoff and water quality data that is urgently required for modelling activities, such as determining progress towards achieving the Reef 2050 Water Quality Improvement Plan targets. This study provides empirical data from the Fitzroy Basin to determine the effects of grazing management practices on paddock scale water quality. More specifically the study aims to:

1) Quantify the impact of conservative and heavy cattle grazing pressures on hydrology and both event mean concentrations (EMCs) and loads of total suspended solids, nitrogen and phosphorus in hillslope runoff over four hydrological years (2015 to 2018);
2) Determine the anthropogenic impact of cattle grazing by comparing hydrology and both EMCs and loads of total suspended solids, nitrogen and phosphorus in hillslope runoff from a conservatively grazed pasture and virgin brigalow woodland which is representative of the pre-European landscape; and
3) Quantify the impact of conservative and heavy cattle grazing pressures on pasture biomass and ground cover over four hydrological years (2015 to 2018).

2. Methods

2.1. Site description

This study was undertaken at the Brigalow Catchment Study which is representative of both the Fitzroy Basin and the Brigalow Belt bioregion (Cowie et al., 2007) (Fig. 1). It is a paired, calibrated catchment study located near Theodore in central Queensland (24°48′S and 149°47′E), Australia, which was established in 1965 to quantify the impact of land development for agriculture on hydrology, productivity and resource condition (Cowie et al., 2007). The hydrological cycle of this study site is extensively documented (Silburn et al., 2009; Thornton et al., 2007; Thornton and Yu, 2016), as are the impacts of land clearing and land use change on runoff water quality (Elledge and Thornton, 2017; Thornton and Elledge, 2016; Thornton and Elledge, 2013). Data from this site is representative of hillslope runoff and erosion processes without any scalds, gullies, streams or streambanks.

In its native state, the study 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). This vegetation association is colloquially known as brigalow scrub (Cowie et al., 2007). The extant uncleared vegetation of the Brigalow Catchment Study is classified as regional ecosystems 11.4.8, *Eucalyptus cambageana* woodland to open forest with *Acacia harpophylla* or *Acacia argyrodendron* on Cainozoic clay plains, and 11.4.9, *Acacia harpophylla* shrubby woodland with *Terminalia oblongata* on Cainozoic clay plains (The State of Queensland, 2020e). Slope of the land averages 2.5% (range 1.8% to 3.5%) for Catchments 1 and 3 (Cowie et al., 2007), and based on an aerial LiDAR survey of the Brigalow Catchment Study in 2019, slope of Catchment 5 averages 5.7%. Soils are an association of Vertosols, Dermosols and Sodosols which are representative of 67% of the Fitzroy Basin under grazing; that is, 28% Vertosols, 28% Sodosols and 11% Dermosols (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. Site history and monitoring period

The Brigalow Catchment Study can be separated into four experimental stages: Stage I, calibration of three catchments in an uncleared state from 1965 to 1982; Stage II, development of two catchments for agriculture from 1982 to 1983; Stage III, comparison of cropping and grazing land use to virgin brigalow scrub from 1984 to 2010; and Stage IV, a comparison of leguminous and non-leguminous pastures to virgin brigalow scrub during the adaptive land management phase from 2010 to 2018. 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). Data in this study is from Catchments 1, 3 and 5 during the adaptive land management phase for the 2015 to 2018 hydrological years (01 October 2014 to 30 September 2018). Catchments 1 and 3 were established during Stage I and Catchment 5 was incorporated into the long-term Brigalow Catchment Study during Stage IV. Table 1 outlines the land use history of these catchments over the four experimental stages, Fig. 2 shows the location of these three catchments within the landscape, and Table 2 characterises the catchments and the treatments applied over this four year study.

Since the commencement of the Brigalow Catchment Study in 1965, Catchment 1 has been retained in a virgin uncleared state to provide a control treatment representative of the Brigalow Belt bioregion in its pre-European condition. Catchment 3 remained uncleared during Stage I. During Stage II it was cleared by bulldozer and chain in March 1982,

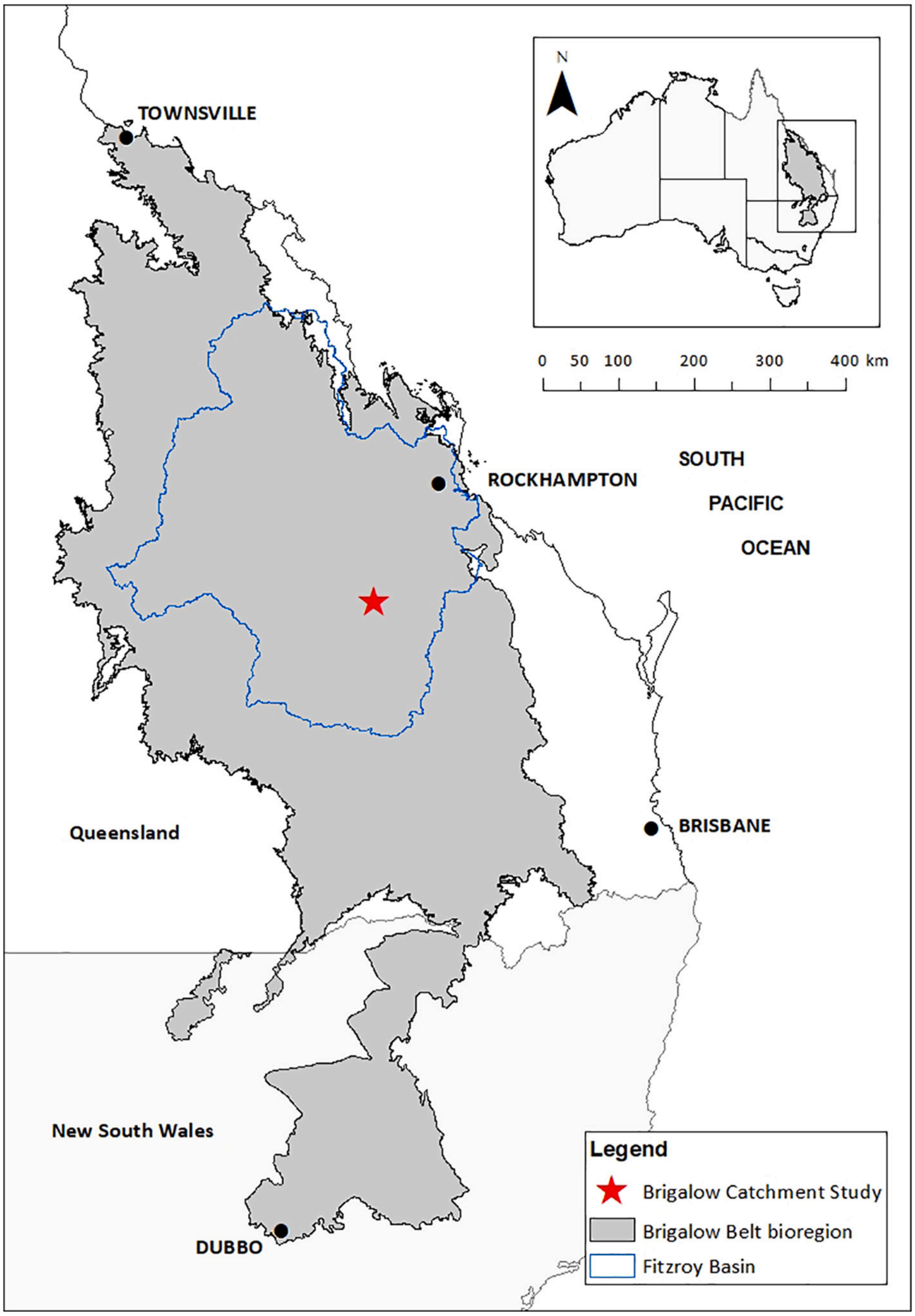


Fig. 1. Location of the Brigalow Catchment Study within the Brigalow Belt bioregion of central Queensland, Australia.

Table 1
Land use history of the three catchments monitored over the 2015 to 2018 hydrological years.

Catchment	Land use by experimental stage			
	Stage I	Stage II	Stage III	Stage IV
	Jan 1965 to Mar 1982	Mar 1982 to Sep 1983	Sep 1984 to Jan 2010	Jan 2010 to Oct 2018
Catchment 1	Brigalow scrub	Brigalow scrub	Brigalow scrub	Brigalow scrub
Catchment 3	Brigalow scrub	Development	Grass pasture	Grass pasture
Catchment 5	Not monitored	Not monitored	Not monitored	Grass pasture

the fallen timber burnt in October 1982 and then the catchment planted to buffel grass (*Cenchrus ciliaris*) pasture in November 1982.

Although all catchments reported in this study were previously part of the former Queensland Department of Primary Industries' Brigalow Research Station, Catchment 5 has a longer history of agricultural land use as it was not incorporated into the Department of Resources' Brigalow Catchment Study until 2014. Aerial photography shows that Catchment 5 was virgin brigalow scrub in 1965 but in a cleared state

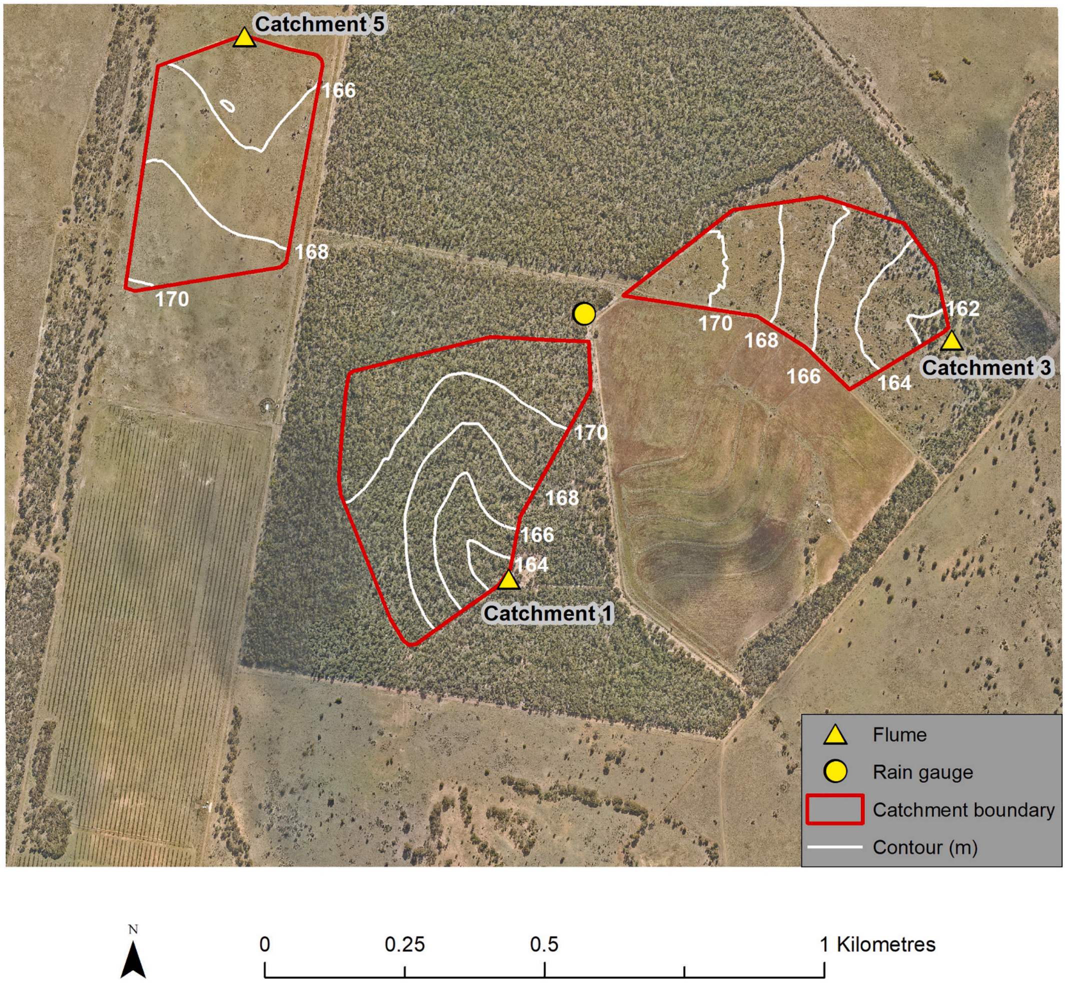


Fig. 2. Aerial photograph of the Brigalow Catchment Study which shows catchment boundaries, topography and location of monitoring equipment.

Table 2
Description of the three catchments monitored over the 2015 to 2018 hydrological years.

Parameter	Brigalow scrub	Conservative grazing	Heavy grazing
Alternative catchment name	Catchment 1	Catchment 3	Catchment 5
Soil type (% of catchment)	Vertosols and Dermosols (70%), Sodosols (30%)	Vertosols and Dermosols (70%), Sodosols (30%)	Vertosols and Dermosols (93%), Sodosols (7%)
Slope	2.5%	2.5%	5.7%
Land use	Virgin brigalow scrub	Improved grass pasture	Improved grass pasture
Cattle stocking philosophy	Ungrazed control	Conservative stocking rate	Heavy stocking rate
Catchment area (ha)	16.8	12.7	12.0
Total grazed area (ha)	Not applicable	17.0	25.0
Pasture spelling philosophy	Ungrazed control	Wet season spell	Limited spelling
Pasture biomass philosophy	Not applicable	Minimum 1000 kg/ha	No minimum limit
Photo			

planted to pasture in 1969, 1977 and 1984 (Commonwealth of Australia, 1969; The State of Queensland, 1965, 1977, 1984). It was a common management practice to have a period of cropping following the initial development of improved pasture on brigalow lands to physically control regrowth of brigalow suckers (Johnson, 1968; Johnson and Back, 1974). Use of this strategy at the Brigalow Research Station was demonstrated by land use maps in annual reports and program reviews which classify Catchment 5 as cultivation in 1988 and

1989, in addition to written records for the planting of forage sorghum in 1989 and barley in both 1990 and 1991 (Queensland Department of Primary Industries, 1988, 1989, 1990, 1991). Aerial photography in 1991 shows the catchment in a tilled state which supports the written records (The State of Queensland, 1991). Catchment 5 was then planted to buffel grass (*Cenchrus ciliaris*) and purple pigeon grass (*Setaria incrassata*) in January 1992 which remains today (Queensland Department of Primary Industries, 1992).

Beef cattle commenced grazing Catchment 3 in December 1983 at a stocking rate of 0.45 adult equivalent (AE)/ha/yr which decreased to 0.26 AE/ha/yr over the next 21 years (Radford et al., 2007). An adult equivalent is considered to be a non-lactating animal of 450 kg live weight (McLean and Blakeley, 2014). Stocking rates varied between 0.06 and 0.23 AE/ha/yr from February 2005 to September 2011, averaging 0.14 AE/ha/yr. The catchment was spelled from September 2011 to December 2013, and then grazed at 0.19 AE/ha/yr from December 2013 to February 2014.

While not incorporated into the Brigalow Catchment Study until 2014, management of Catchment 5 was taken over by the Department of Resources in 2008. Although exact stocking rates prior to this period were unknown, cattle stocking philosophies for the broader Brigalow Research Station can be used as a surrogate. In 1965 it was stated that the Brigalow Research Station could carry 800 head of cattle once cleared and developed (Queensland Department of Primary Industries, 1965). This was later revised to an aspirational range from 800 to 1000 head of grown cattle in 1976 (Stringer, 1976) which remained until 1989 while land development was still in progress (Nasser, 1986; Queensland Department of Primary Industries, 1987, 1988, 1989). Carrying capacities were not published in annual reports from 1990 to 1995; however, from 1996 to the final technical report in 2004 it was stated that the station had a sustainable carrying capacity of 1200 adult equivalents (Jeffery and Loxton, 1998, 1999; Loxton et al., 1994; Loxton and Boadle, 1995, 1996, 1997; Loxton and Forster, 2000; Queensland Department of Primary Industries, 1990, 1991, 1992; Sinclair and White, 2004).

Early carrying capacities expressed as grown cattle can be converted to adult equivalents using carcase specifications for the brigalow lands of Queensland combined with dressing percentages. Carcase weights averaged 269 kg (range 250 to 300 kg) (Strachan, 1976) and an appropriate dressing percentage to convert live weight to carcase weight is 53% (Meat and Livestock Australia, 2017b). The average dressing percentage of 53% for heavy steers with a fat score of three was selected, as Strachan (1976) states that steers with a low fat carcass were the most common animal produced for slaughter. For example, a carcase weight of 269 kg and a dressing percentage of 53% suggests that the live weight of a grown animal was about 508 kg, equal to 1.13 adult equivalents. Thus, the aspiration to carry 800 to 1000 head of grown cattle equates to carrying capacities of 896 and 1120 adult equivalents, respectively, which were both lower than the 1200 adult equivalent carrying capacities reported from 1996 to 2004. These carrying capacities translate into surrogate stocking rates of 0.33 AE/ha/yr, 0.41 AE/ha/yr and 0.45 AE/ha/yr, respectively (Fig. 3).

Although these calculated stocking rates can be used as a surrogate for Catchment 5 over one or more decades, they are less suited to estimate annual stocking rates. Brigalow Research Station documents from 1990 to 2004 noted an increase in both area of pasture and annual livestock returns over time (Jeffery and Loxton, 1998, 1999; Loxton et al., 1994; Loxton and Boadle, 1995, 1996, 1997; Loxton and Forster, 2000; Queensland Department of Primary Industries, 1990, 1991, 1992; Sinclair and White, 2004). Thus, a surrogate annual stocking rate for Catchment 5 can be calculated as the number of cattle on the entire station during the year divided by the total area of available pasture to yield an AE/ha/yr (Fig. 3). Annual livestock returns for the station reported both young cattle less than one adult equivalent and older cattle greater than one adult equivalent, so it is reasonable to assume that the total number of cattle reported could be expressed as adult equivalents.

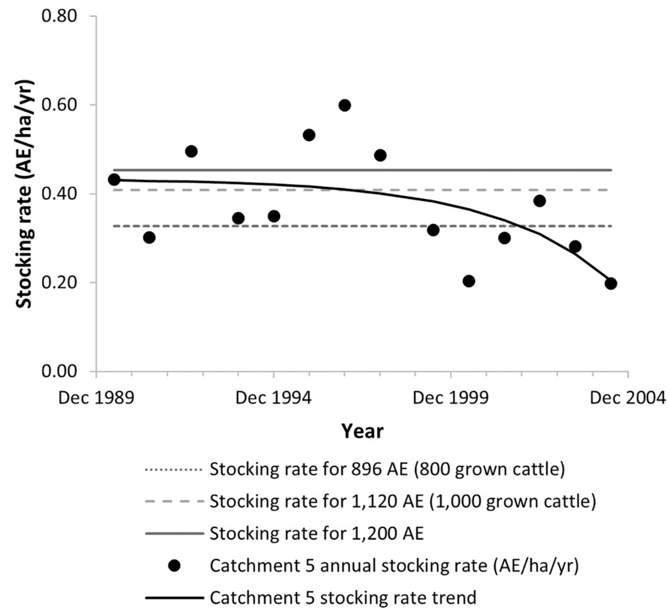


Fig. 3. Aspirational and actual stocking rates for the Brigalow Research Station used to estimate stocking rates from Catchment 5 prior to the commencement on this study in 2014.

Annual calculations suggest that stocking rates for Catchment 5 decreased from 0.43 AE/ha/yr in 1990 to 0.20 AE/ha/yr in 2004 (Fig. 3). Limited grazing occurred in Catchment 5 from 2004 until discussions to close the Brigalow Research Station in 2008. The catchment was spelled from June 2008 to July 2012 when it was grazed at 0.45 AE/ha/yr until September 2012, then grazed at 0.11 AE/ha/yr until December 2012.

2.3. Treatments

Over the four hydrological years of this study, Catchment 1 was retained in its virgin uncleared condition supporting brigalow scrub. Vertosols and Dermosols (clay soils) occupy approximately 70% of the catchment and Sodosols occupy the remaining 30% (Cowie et al., 2007; Isbell, 1996). Catchment 3 continued as a conservatively grazed catchment with a buffel grass (*Cenchrus ciliaris* cv. Biloela) pasture. Vertosols and Dermosols (clay soils) occupy approximately 58% of the catchment and Sodosols occupy the remaining 42% (Cowie et al., 2007; Isbell, 1996). Catchment 5 commenced as a heavily grazed catchment with an existing buffel grass (*Chenchrus ciliaris*) and purple pigeon grass (*Setaria incrassata*) pasture. Vertosols occupy approximately 93% of the catchment and Sodosols occupy the remaining 7% (Isbell, 1996). The Australian Soil Classification for Catchment 5 was determined by Land Resource Officers from the Department of Resources based on the soil survey of Webb (1971), the soil chemistry of Webb et al. (1977) and soil descriptions undertaken in 2018 which were extracted from the Soil And Land Information (SALI) system (Biggs et al., 2000).

The two pastures were spelled prior to the commencement of this study in October 2014. The conservatively grazed pasture was spelled from February 2014, while the heavily grazed pasture was spelled from December 2012. Conservative grazing pressure reflected the safe long-term carrying capacity for rundown buffel grass pasture, whereas heavy grazing pressure reflected stocking rates recommended for newly established buffel grass pasture. The Brigalow Catchment Study has been managed to maintain good (A) land condition and the estimated long-term carrying capacity was 0.22 AE/ha/yr (range 0.19 to0.27 AE/ha/yr). This estimate was obtained from the Long Paddock FORAGE system which provides a property specific report based on climate data, satellite imagery and modelled pasture growth (The State of

Queensland, 2021). Whereas published recommended stocking rates are about 0.50 AE/ha/yr for newly established buffel grass pasture and about 0.33 AE/ha/yr 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).

Stocking rates during this study were set based on measured pasture biomass, with pasture utilisation targets of less than 30% in the conservatively grazed pasture and greater than 50% in the heavily grazed pasture. Dietary intake was considered to be 2.2% of animal live weight (Minson and McDonald, 1987). Actual stocking rates for this study have been presented as adult equivalents per hectare per year (AE/ha/yr) to account for differences in the size of cattle and the length of time the pastures were grazed (Table 3). 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.

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 HL flume with a 3.9 × 6.1 m approach box (Brakenseik et al., 1979). 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).

The 18 year calibration period for the three long-term catchments in Stage I meant that runoff from Catchment 3 can be estimated from measured runoff from Catchment 1 (Thornton et al., 2007). A calibration period for Catchment 5 was not possible as it had been developed for agriculture sometime between 1965 and 1969, which was at least 40 years prior to its inclusion in the study. Thus, although Catchment 5 has its own unique hydrological characteristics, its relationship to Catchments 1 and 3 in an uncleared state is unknown.

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).

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 the event-based water quality loads, and load in kg/ha was calculated by accounting for 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 site EMC for each catchment using the method of Elledge and Thornton (2017). 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. This method was applied to all events from brigalow scrub as flows were too small to trigger auto-samplers. 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.

Table 3
Annual stocking rates in adult equivalents (AE) per hectare per year for the two pasture treatments.

Year	Stocking rate (AE/ha/yr)	
	Conservative grazing	Heavy grazing
2013	Destocked	0.09
2014	0.19	Destocked
2015	0.20	0.83
2016	0.13	0.20
2017	0.19	0.26
2018	Destocked	0.86

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

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

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

Parameter	Method
Total suspended solids	Method 18211 based on gravimetric quantification of solids in water
Total nitrogen and total dissolved nitrogen	Method 13802 by simultaneous persulfate digestion
Oxidised nitrogen	Method 13798 based on flow injection analysis of nitrogen as oxides
Ammonium-nitrogen	Method 13796 based on flow injection analysis of nitrogen as ammonia
Total phosphorus and total dissolved phosphorus	Method 13800 by simultaneous persulfate or Kjeldahl digestion
Dissolved inorganic phosphorus	Method 13799 by flow injection analysis

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

Parameter	Equation
Particulate nitrogen	Total nitrogen minus total dissolved nitrogen
Dissolved inorganic nitrogen	Oxidised nitrogen plus ammonium-nitrogen
Dissolved organic nitrogen	Total dissolved nitrogen minus dissolved inorganic nitrogen
Particulate phosphorus	Total phosphorus minus total dissolved phosphorus
Dissolved organic phosphorus	Total dissolved phosphorus minus dissolved inorganic phosphorus

2.6. 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.

2.7. Ground cover

Ground cover from the total grazed area of the two pasture catchments was compared from October 2012 to October 2018 using VegMachine® (Fitzroy Basin Association, 2018). VegMachine is a simple tool for interrogating large raster time series ground cover datasets derived from Landsat satellite imagery (Beutel et al., 2019; Terrestrial Ecosystem Research Network, 2010). The analysis of ground cover at or near ground level, which excludes taller cover such as tree and shrub canopies, required individual spatial polygons to define each catchment (Beutel et al., 2019). Polygons for the conservatively and heavily grazed catchments were defined as the fence line boundary for each paddock, which was identified via satellite imagery. Both catchment polygons were then manually imported into VegMachine and the "*Polygon Comparison*" tool used to perform a ground cover analysis of the conservatively and heavily grazed catchments. Seasonal deciles were also reported for total (green and non-green) cover, where total cover and bare ground equal 100%. These were calculated automatically within VegMachine using quarterly data from Autumn (March to May) 1988 to Summer (December to February) 2012/2013 as a baseline, with every season 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) 2015 was ranked against total cover from all the spring images from the baseline period.

2.8. Benchmarking ground cover to the Fitzroy Basin

VegMachine was also used to determine how representative ground cover from the Brigalow Catchment Study was to the wider Fitzroy Basin. This was achieved by comparing the conservatively and heavily grazed catchments to the six sub-basins of the Fitzroy Basin; that is, the Dawson, Comet, Nogoa, Isaac, Mackenzie and Fitzroy. Sub-basin comparisons were undertaken to better represent the range of covers within the Fitzroy Basin. Spatial layers for VegMachine analysis were prepared using a multi-step process in ArcGIS (Environmental Systems Research Institute, 2020):

1) Boundaries for the six sub-basins were obtained from the "*Basin sub areas - Queensland*" spatial layer, accessed via the Queensland Spatial Catalogue (QSpatial) (The State of Queensland, 2020c).
2) Landscapes that were comparable to the Brigalow Catchment Study were identified by interrogating the Regional Ecosystem Description Database to return Regional Ecosystems that contained the term "harpophylla" in the description (The State of Queensland, 2019). These landscapes historically supported brigalow (*Acacia harpophylla*) vegetation communities on predominantly clay soils.
3) The "*Grazing land management land types V5*" spatial layer (accessed via QSpatial) was clipped to the six sub-basin boundaries defined in step one. This layer was used by VegMachine to determine the appropriate ground cover data for polygon comparisons.
4) The layer produced in step three was further clipped to the Regional Ecosystems identified in step two by using a definition query for "harpophylla" within the attribute table.
5) The "*Land use mapping – 1999 to 2017*" spatial layer (accessed via QSpatial) was clipped to landscapes with a secondary land use of "grazing" in the 2017 data to provide a relevant comparison to the grazed pasture catchments in this study. This layer was further clipped to six sub-basin boundaries defined in step one.
6) The Regional Ecosystem layer created in step four was further clipped to the grazing layer produced in step five. The result was a spatial layer for each sub-basin that had multiple polygons displaying only grazing land supporting Regional Ecosystems containing *Acacia harpophylla*.
7) The layer produced in step 6 retained Regional Ecosystem classifications within the attribute table under the identifier "stratum". This stratum identifier is required by VegMachine to determine the appropriate ground cover data for polygon comparison and was listed as "FT05" or brigalow with melonholes for the Brigalow Catchment Study (Fitzroy Basin Association, 2018; The State of Queensland, 2021). For each sub-basin, the stratum identifier FT05 was assigned to every polygon and then all polygons dissolved into a single polygon. The final result was a single polygon for each sub-basin displaying only grazing land supporting Regional Ecosystems containing *Acacia harpophylla* with the stratum identifier FT05.

Polygons for the conservatively and heavily grazed catchments in addition to polygons for all six sub-basins of the Fitzroy Basin were manually imported into VegMachine and the "*Polygon Comparison*" tool was used to perform ground cover analyses. Comparative ground cover analyses only considered time periods where ground cover observations, including deciles, occurred for all polygons.

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 (Fig. 4). 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).

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 catchment (Fig. 5). 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

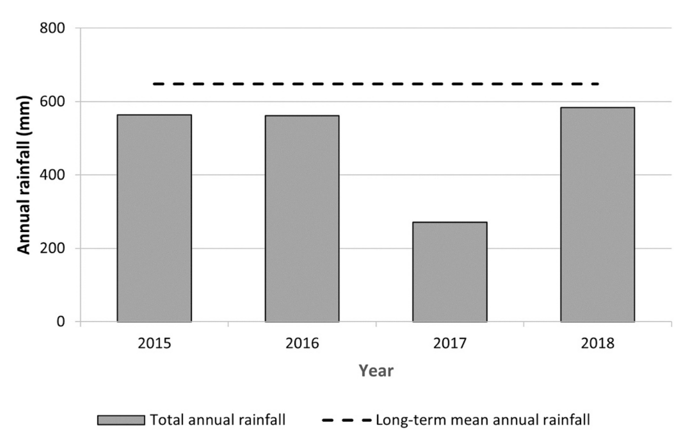


Fig. 4. Total annual hydrological year rainfall for 2015 to 2018 relative to the long-term mean annual rainfall for the Brigalow Catchment Study.

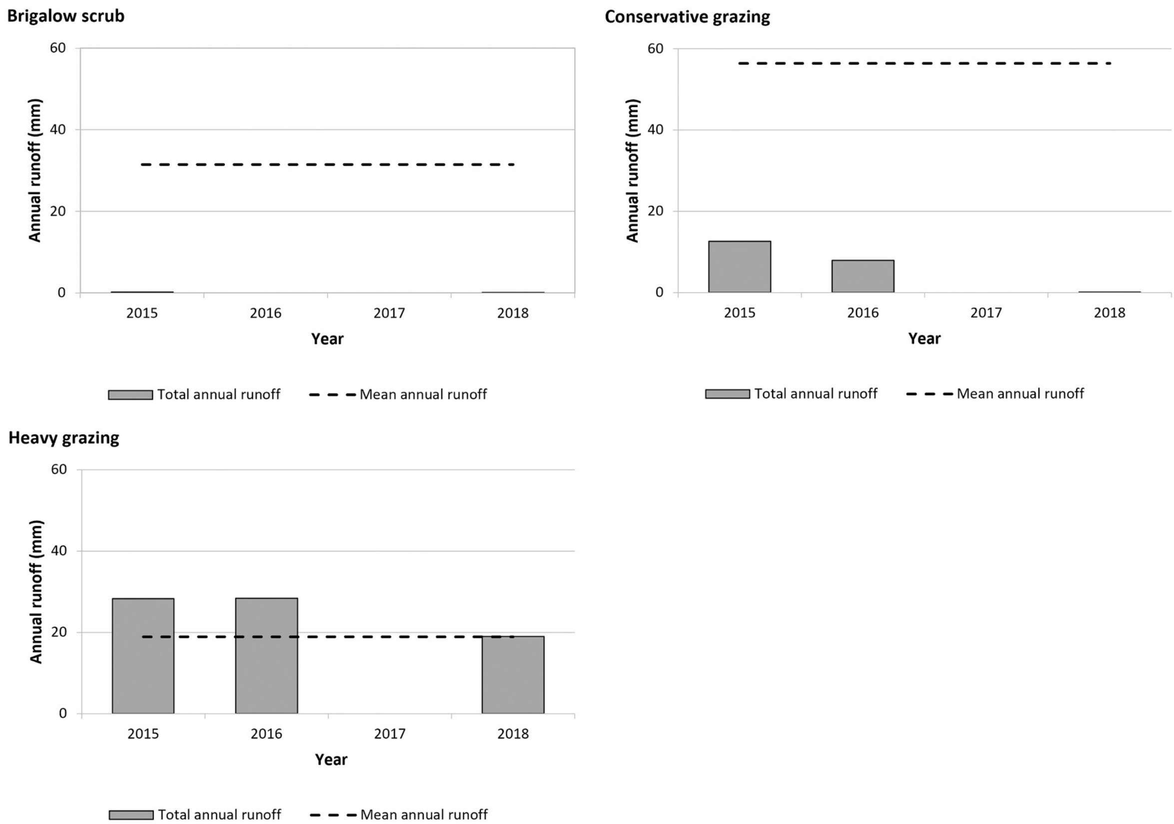


Fig. 5. Total annual hydrological year runoff for 2015 to 2018 relative to mean annual runoff for the three catchments. Mean annual runoff for the brigalow scrub and conservatively grazed catchments were based on 34 years (1985 to 2018) data, but only four years data (2015 to 2018) for the heavily grazed catchment.

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/h)	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/h)	2015	0.1	3.1	6.5
	2016	0	1.0	2.6
	2017	0	0	0
	2018	0.1	0.1	4.7

in 2017, and in 2018 was in the 15th percentile.

Hydrological data and water quality sampling effort for 2015 to 2018 are summarised in Table 7. 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 at least double the runoff of 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.

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/h)	2015	0.2
	2016	0
	2017	0
	2018	0.4
Increase in average peak runoff rate under pasture (mm/h)	2015	2.4
	2016	1.0
	2017	0
	2018	0

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).

3.2. *Water quality*

3.2.1. *Total suspended solids*

Mean annual EMC for total suspended solids was greater from conservatively than heavily grazed pasture (Table 9). Mean annual load of total suspended solids from the heavily grazed pasture was 3.2 times greater than from the conservatively grazed pasture (Fig. 6, Table 10). Brigalow scrub had no EMCs as flows were too small to collect runoff

Table 9
Event mean concentrations of total suspended solid, nitrogen and phosphorus parameters in runoff from 2015 to 2018.

Parameter	Event mean concentration (mg/L)		
	Brigalow scrub	Conservative grazing	Heavy grazing
Total suspended solids	No data	278	235
Total nitrogen	No data	6.49	2.39
Particulate nitrogen	No data	3.40	1.14
Total dissolved nitrogen	No data	3.08	1.25
Dissolved organic nitrogen	No data	1.28	0.66
Dissolved inorganic nitrogen	No data	1.81	0.59
Total phosphorus	No data	0.81	0.49
Particulate phosphorus	No data	0.50	0.22
Total dissolved phosphorus	No data	0.31	0.27
Dissolved organic phosphorus	No data	0.05	0.04
Dissolved inorganic phosphorus	No data	0.26	0.23

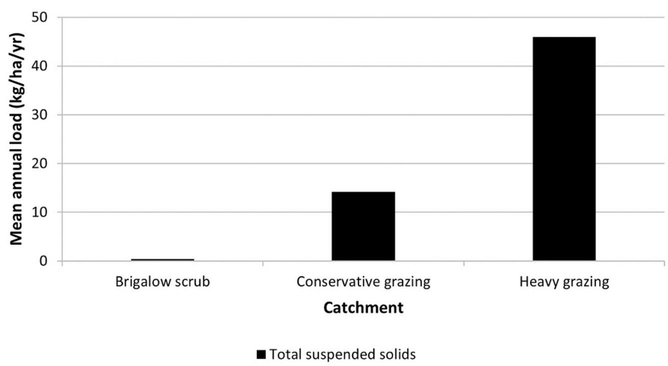


Fig. 6. Mean annual load of total suspended solids in runoff from 2015 to 2018.

Table 10
Mean annual loads of total suspended solid, nitrogen and phosphorus parameters in runoff from 2015 to 2018.

Parameter	Mean annual load (kg/ha)		
	Brigalow scrub	Conservative grazing	Heavy grazing
Total suspended solids	0.4	14.2	46.0
Total nitrogen	0.01	0.29	0.46
Particulate nitrogen	<0.01	0.14	0.21
Total dissolved nitrogen	0.01	0.15	0.26
Dissolved organic nitrogen	<0.01	0.07	0.13
Dissolved inorganic nitrogen	<0.01	0.08	0.12
Total phosphorus	<0.01	0.04	0.10
Particulate phosphorus	<0.01	0.02	0.04
Total dissolved phosphorus	<0.01	0.02	0.06
Dissolved organic phosphorus	<0.01	0.00	0.01
Dissolved inorganic phosphorus	<0.01	0.01	0.05

samples whereas loads were estimated by multiplying the long-term site EMC by observed flow.

3.2.2. Nitrogen

Mean annual EMC for total, particulate and total dissolved nitrogen were greater from conservatively than heavily grazed pasture (Table 9). Mean annual load of total nitrogen from the heavily grazed pasture was 1.6 times greater than from the conservatively grazed pasture (Fig. 7, Table 10). 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 11).

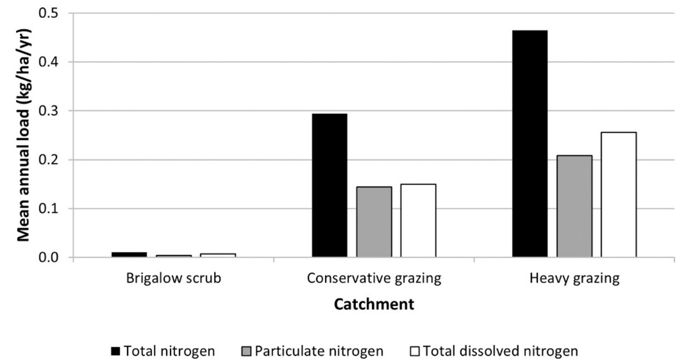


Fig. 7. Mean annual load of total, particulate and dissolved nitrogen in runoff from 2015 to 2018.

The mean annual EMC for dissolved organic and inorganic nitrogen were greater from conservatively grazed pasture than heavily grazed pasture (Table 9). Mean annual load of total dissolved nitrogen from the heavily grazed pasture was 1.7 times greater than from conservatively grazed pasture (Fig. 8, Table 10). 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.

3.2.3. Phosphorus

The mean annual EMC for total, particulate and total dissolved phosphorus were greater from conservatively than heavily grazed pasture (Table 9). Mean annual load of total phosphorus from the heavily grazed pasture was 2.6 times greater than from conservatively grazed pasture (Fig. 9, Table 10). 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 12).

The mean annual EMC for dissolved inorganic and organic phosphorus was greater from conservatively grazed pasture than heavily grazed pasture (Table 9). Mean annual load of total dissolved

Table 11
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

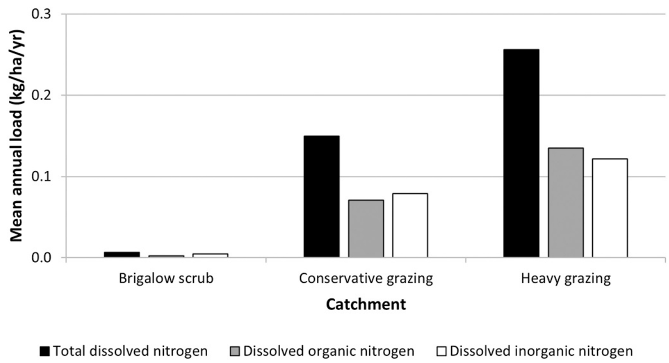


Fig. 8. Mean annual load of dissolved nitrogen fractions in runoff from 2015 to 2018.

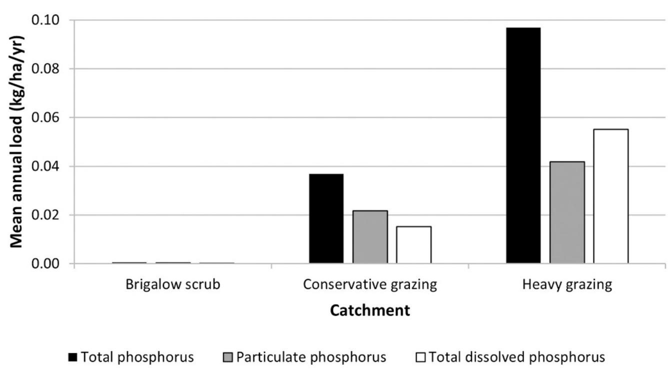


Fig. 9. Mean annual load of total, particulate and dissolved phosphorus in runoff from 2015 to 2018.

Table 12
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

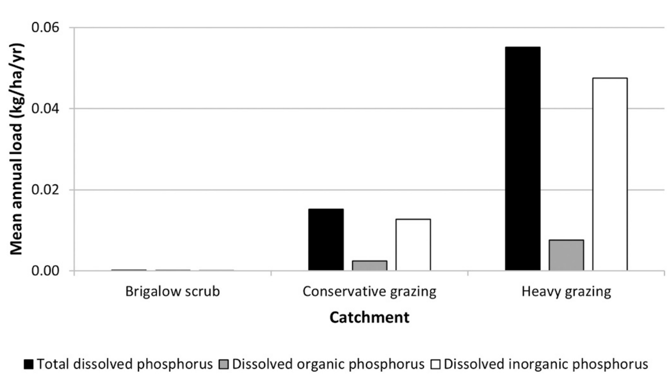


Fig. 10. Mean annual load of dissolved phosphorus fractions in runoff from 2015 to 2018.

phosphorus from the heavily grazed pasture was 3.6 times greater than from conservatively grazed pasture (Fig. 10, Table 10). 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.

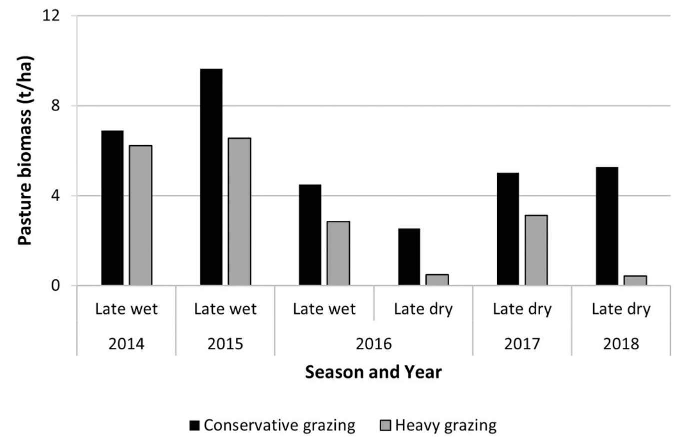


Fig. 11. Pasture biomass in the two pastures from 2015 to 2018.

3.3. Pasture biomass

Overall, the heavily grazed catchment had lower pasture biomass than the conservatively grazed catchment (Fig. 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 (Fig. 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.

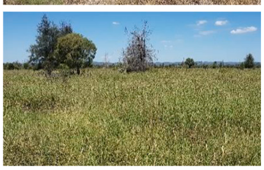
In the 2017 late dry season, biomass had increased to 5.0 t/ha under conservative grazing and 3.1 t/ha under heavy grazing (Fig. 11). Pasture biomass in the heavily grazed catchment increased to 62% of that from the conservatively grazed catchment, similar to the 2015 and 2016 late wet seasons. In the 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.

Table 13 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. In each instance the photographs show that the heavily grazed pasture had less pasture biomass and ground cover than the conservatively grazed pasture.

3.4. 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 (Fig. 12). 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 October 2018, the amount of bare ground in the

Table 13
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				
2016				
2017				
2018				

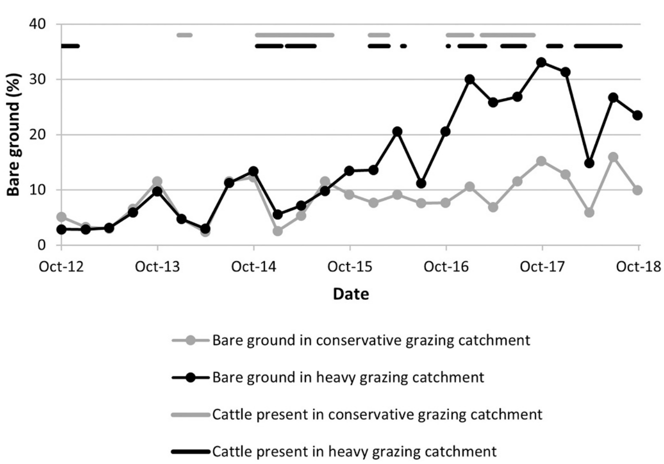


Fig. 12. Measurements of bare ground in the two pastures related to periods of cattle stocking.

heavily grazed pasture (23.5%) was 2.4 times greater than in the conservatively grazed pasture (9.9%). Ground cover in the conservatively grazed pasture remained relatively constant during the study with 95% of the pasture having cover levels of 80% or higher in October 2018. However, cover levels across 95% of the heavily grazed pasture decreased to 57% or higher by January 2018 before increasing to 69% or higher in October 2018, which was slightly lower than 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.

3.5. Benchmarking ground cover to the Fitzroy Basin

Regional Ecosystems that contain brigalow (*Acacia harpophylla*) account for 32% of the Fitzroy Basin. Grazing is the predominant land use in these Regional Ecosystems, as it occurs on 86% of land that historically supported *Acacia harpophylla* in the Fitzroy Basin (Fig. 13).

VegMachine ground cover analysis provides outputs from May 1990. Since then, median VegMachine derived ground cover for the conservatively grazed catchment exceeded the lowest 80th percentile for the six Fitzroy sub-basins 95% of the time and exceeded the lowest 95th percentile 85% of the time (Fig. 14). Since the heavy grazing treatment was planted to the current pasture in 1992 until commencement of this study in 2014, median ground cover in the catchment equalled or exceeded the conservatively grazed catchment 40% of the time. During this period, ground cover exceeded the lowest 80th percentile for the six Fitzroy sub-basins 89% of the time and exceeded the lowest 95th percentile 70% of the time. Within five years of heavy grazing commencing, ground cover in that catchment was within the 5th percentile range of covers for the six Fitzroy sub-basins 44% of the time (Fig. 14).

4. Discussion

4.1. Stocking rates and safe long-term carrying capacity

Published recommended stocking rates for buffel grass pastures on brigalow lands vary from 0.1 AE/ha/yr to 0.5 AE/ha/yr (Lawrence and French, 1992), with observed stocking rates reported to be in the same range (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 0.5 AE/ha/yr on newly established buffel grass pastures and 0.33 AE/ha/yr 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.,

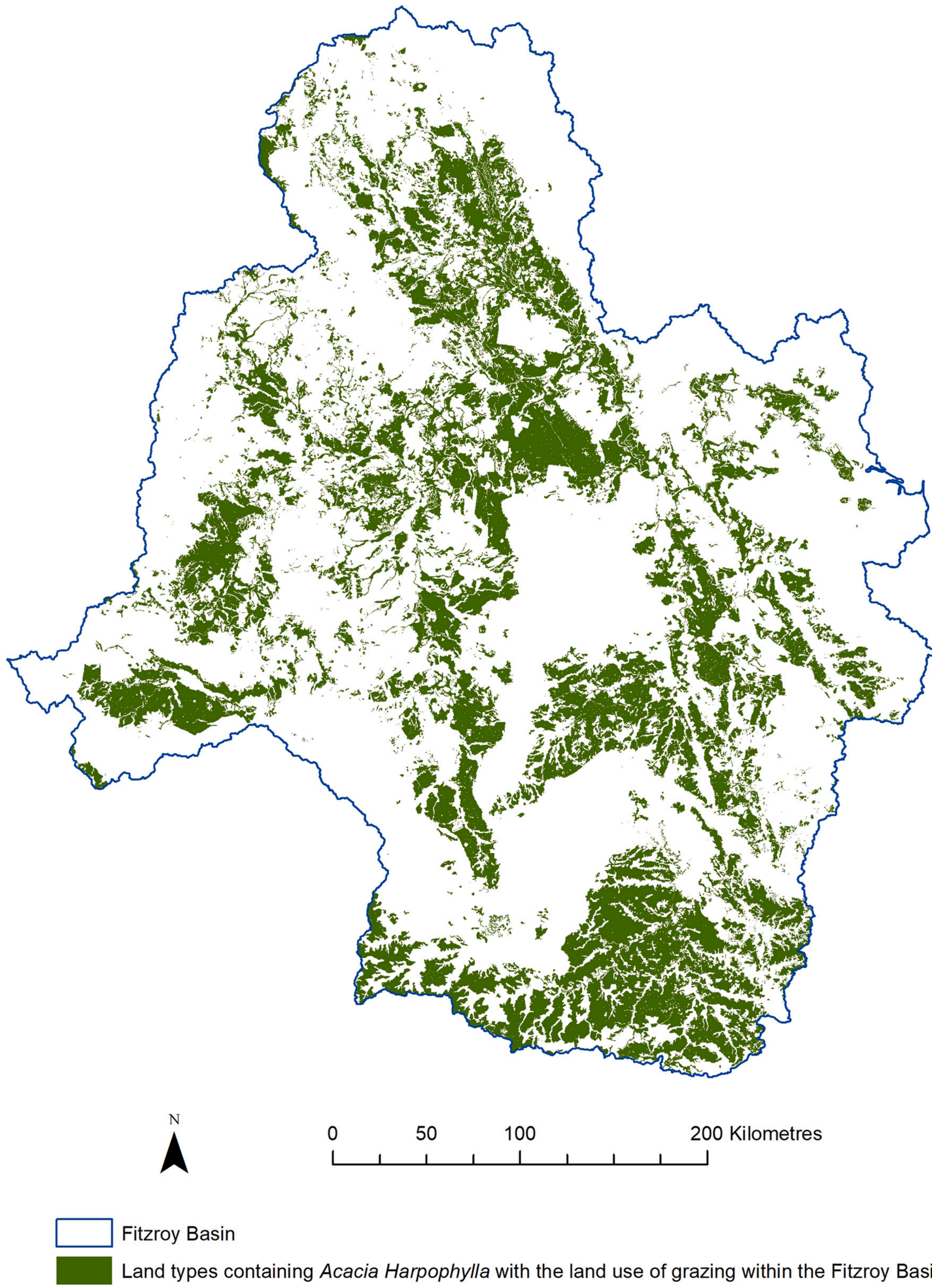


Fig. 13. Land types containing brigalow (*Acacia harpophylla*) with the land use of grazing (green) within the Fitzroy Basin (blue outline). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2007); however, Partridge et al. (1994) states that stocking rates should be adjusted to achieve daily weight gains of 0.4 kg/head on rundown pastures as the plants are more likely to be damaged at higher stocking rates.

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. Historically, stocking rates for this pasture were 0.45 AE/ha/yr on newly established buffel grass pasture when the study commenced, which decreased to 0.26 AE/ha/yr over the next 21 years (Radford et al., 2007). The average long-term (1984 to 2017) stocking rate was 0.30 AE/ha/yr (unpublished data). Daily weight gains in the order of 0.5 kg/head were achieved initially and have been

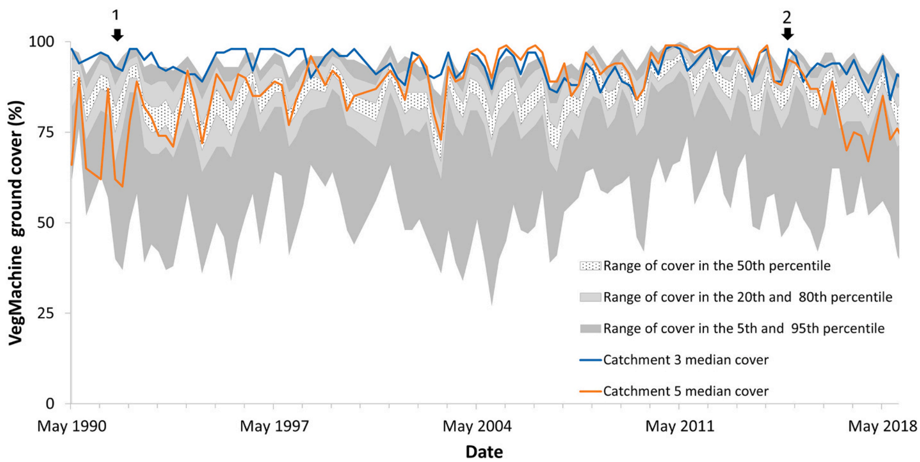


Fig. 14. Median satellite derived ground cover for the conservatively (blue line) and heavily (orange line) grazed catchments of the Brigalow Catchment Study compared to the range of cover percentiles for the Fitzroy Basin. Arrow 1 indicates planting of pasture in Catchment 5 following three years of cropping and arrow 2 indicates the commencement of heavy grazing in Catchment 5. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

obtained periodically since (Radford and Thornton, 2011; Radford et al., 2007). However, maintaining the 0.45 AE/ha/yr 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 AE/ha/yr. 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. For three decades post-clearing but prior to the inclusion of Catchment 5 into the Brigalow Catchment Study, historical stocking rates were about 0.40 AE/ha/yr. These stocking rates decreased over the next decade to less than 0.25 AE/ha/yr, followed by extensive spelling over the next eight years. This management history is in line with published recommended and observed industry stocking rates for brigalow lands, which suggests that sustained heavy grazing prior to inclusion in this study was unlikely.

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 VegMachine ground cover analysis, which shows that while ground cover in the heavily grazed pasture of the Brigalow Catchment Study was often in the 5th percentile for grazed *Acacia harpophylla* landscapes in the Fitzroy Basin, ground cover was still higher than some properties within similar landscapes. Thus, the heavily grazed pasture in this study may overestimate pasture biomass and ground cover and underestimate hydrology and water quality compared to some properties.

The concept of a 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 pasture 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). A safe long-term carrying capacity can be estimated using pasture biomass, dietary intake requirements of cattle and pasture utilisation rates. For the conservatively grazed pasture, a safe long-term carrying capacity was 0.29 AE/ha/yr based on a long-term pasture biomass of 3500 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). This was similar to the lower estimate of long-term carrying capacity of 0.27 AE/ha/yr for the Brigalow Catchment Study determined by the FORAGE system (The State of Queensland, 2021). This was expected given the Aussie GRASS model (Carter et al., 2000) used in the FORAGE system is based on the GRASP pasture simulation model (Rickert et al., 2000), and both models have been informed by long-term BOTANAL pasture assessments, stocking rate and animal production data from the Brigalow Catchment Study (Dalal et al., 2021). GRASP pasture simulation modelling for Catchment 3 shows that in order to maintain a long-term pasture biomass of 3500 kg/ha, an average of about 7400 kg/ha of pasture biomass needs to be grown each year (Dalal et al., 2021). Although a safe long-term carrying capacity can be calculated, stocking rates should still be adjusted annually at the end of the summer growing period to account for pasture biomass. This reduces environmental damage, workload and management stress while benefiting long-term financial viability for the grazing enterprises (Lawrence and French, 1992).

4.2. Effect of grazing pressure on hydrology

The climatic sequence experienced in this study should not be considered atypical. Long-term records for the Brigalow Catchment Study show four consecutive below average rainfall years have occurred previously from 2006 to 2009 (Elledge and Thornton, 2017; Thornton et al., 2007; Thornton and Elledge, 2013, 2014). While the lowest total annual rainfall in the history of the Brigalow Catchment Study occurred in 2017, resulting in no runoff from any catchment, there have been four years between 1965 and 2014 when there was also no runoff from both Catchments 1 and 3 (Elledge and Thornton, 2017; Thornton et al., 2007; Thornton and Elledge, 2013, 2014). This highlights the need for long-term studies in semi-arid landscapes to capture both seasonal and annual rainfall variability, which is the key driver of most landscape processes (Cowie et al., 2007).

From first principles, heavy grazing pressure should decrease ground cover compared to conservative grazing pressure in the same landscape due to increased pasture utilisation and cattle trampling. It was hypothesised that a decline in ground cover combined with the deleterious effects of grazing on soil physical characteristics, such as structure and infiltration rate, would lead to increased runoff. This trend was demonstrated by the findings of Silburn et al. (2011) and Silcock et al. (2005) in the Fitzroy Basin, Bartley et al. (2014) and McIvor et al. (1995) in the Burdekin Basin, and internationally in reviews such as those of van Oudenhoven et al. (2015). Increased runoff is noted as a driver for both increased erosion and nutrient loads in runoff by both Australia studies (Koci et al., 2020; Thornton et al., 2017) and international long-term paired catchment studies, such as those of the Santa Rita Experimental Watershed (Polyakov et al., 2010). For example, the long-term Santa Rita study determined that runoff was the best predictor of sediment yield and explained up to 90% of its variability. As runoff is known to increase with a decline in ground cover and/or biomass (Bartley et al., 2010; Koci et al., 2020; McIvor et al., 1995; Silburn et al., 2011), 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). This body of evidence suggested that the heavy grazing pressure in this study would ultimately lead to increased loads of sediment and nutrients in hillslope runoff compared to conservative grazing. Hillslope erosion of particular concern, as it accounts for 22% of sediment loss from Great Barrier Reef catchments (McCloskey et al., 2021).

Changing land use from virgin brigalow scrub to conservatively grazed pasture at the long-term Brigalow Catchment Study doubled total runoff (Thornton et al., 2007) and increased both average and maximum peak runoff rates by 1.5 times and 3.0 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 this four-year study, the heavily grazed pasture had 2.4 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 represents an absolute anthropogenic increase attributable to land use change.

Although Catchment 5 had a prior history of grazing before its inclusion in the Brigalow Catchment Study, both pasture catchments were managed according to recommended stocking rates. Satellite derived ground cover from VegMachine reflects this cattle stocking philosophy with similar cover for both the conservatively and heavily grazed pastures following the establishment of the current pasture in Catchment 5. Both Catchments 3 and 5 were dominated by clay soils (Vertosols and Dermosols) with a low slope (<6%), so inherent geomorphological differences are unlikely to override the grazing treatment effects on runoff and water quality. Furthermore, evidence that the runoff response from Catchment 5 is a treatment effect was supported by runoff responses from other catchments of the Brigalow Catchment Study.

For example, Catchment 4 of the Brigalow Catchment Study (Thornton and Elledge, 2013) had the same land use history as Catchment 5 until 1998 when it was planted to a leucaena and grass pasture. If the runoff response to the heavy grazing treatment in Catchment 5 during this study was a legacy response to historical land use, then a similar runoff response was expected from Catchment 4. That is, Catchment 4, a conservatively grazed leucaena and grass pasture, would have about triple the runoff of Catchment 3, the conservatively grazed grass pasture. However, Catchment 4 had only 94% of the total runoff from Catchment 3 from 2010 to 2013 (Thornton and Elledge, 2013, 2014); 464 mm and 496 mm, respectively. Similarly, the calibration of the long-term catchments in Stage I showed that the greatest difference in pre-clearing runoff was 28% (Thornton et al., 2007). This is an order of magnitude less than the difference in runoff between Catchments 3 and 5 during this study. Thus, the impacts of heavy grazing pressure on hydrology and water quality were considered to be related to the treatment imposed in Catchment 5 rather than a legacy response to historical sustained heavy grazing.

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. It is also known that the effects of cover on runoff and erosion are more complicated than a simple presence or absence relationship, with additional drivers including the type, distribution and mass of cover (Bartley et al., 2014; Koci et al., 2020). Increased runoff, and subsequently increased loads of nutrients in runoff, were effectively a reduction in plant available water capacity and soil fertility which leads to reduced pasture growth.

Persistent heavy grazing is also known to change the composition of pasture species over time, which leads 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). Thus, runoff, plant available water capacity, soil fertility, 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, but became profitable with less cattle once the perennial grasses recovered. Other research in the Burdekin Basin 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 (Rolfe et al., 2020).

4.3. Effect of grazing pressure on water quality

Heavily grazed pasture had higher loads and lower EMCs for all water quality parameters compared to the conservatively grazed pasture. In years when no runoff occurred from brigalow scrub, total runoff and subsequent loads of total suspended solids and all nutrients from the conservatively grazed pasture represent 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 conservatively grazed pasture during wetter periods and over longer timeframes (Elledge and Thornton, 2017; Thornton and Elledge, 2013, 2014). These trends indicate that increased hillslope runoff, 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). It also reflects previous observations that high EMCs at this site do not necessarily equate to high loads (Thornton and Elledge, 2013).

4.3.1. Total suspended solids

Runoff from heavily grazed pasture had 3.2 times greater loads of total suspended solids than the conservatively grazed pasture. An increase in suspended solids with a decrease in ground cover reflected 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 in this study also showed that ground cover decreased with increased grazing pressure. Despite similar cover levels in the two pastures initially, there was 2.4 times more bare ground in the heavily grazed pasture (23.5%) after four years compared to the conservatively grazed pasture (9.9%). 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 were considerably lower than observed from the conservatively grazed pasture during an extremely wet period from 2010 to 2013

(Thornton and Elledge, 2013), a return to average conditions from 2013 to 2014 (Thornton and Elledge, 2014), and also modelled loads for the period 1984 to 2010 (Elledge and Thornton, 2017). Mean annual load from the three previously reported periods was 258 kg/ha/yr (range 20 to 468 kg/ha/yr). Loads from this study were also lower than more erosive landscapes on shallower soils elsewhere in the Fitzroy Basin (Silburn et al., 2011) and also 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, 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 Brigalow Catchment Study were generally higher than from conservatively grazed pasture when runoff occurred from both catchments (Elledge and Thornton, 2017; Thornton and Elledge, 2013, 2014). This highlights the importance that hydrological characteristics, vegetation type and landscape condition (i.e., ground cover) have on the resulting total suspended solids concentrations and loads. Data from the Brigalow Catchment Study can fill the knowledge gap of water quality from brigalow lands in the Fitzroy Basin to further refine estimations of the impact of grazing land management on Great Barrier Reef water quality.

4.3.2. Nitrogen

Similar to 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 the heavily grazed pasture. This reflects other studies that have reported greater loads of nitrogen from grazed than ungrazed areas and 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 (Thornton and Elledge, 2013, 2014) and over longer timeframes (Elledge and Thornton, 2017); 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.

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, 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, 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 contrasts with 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).

4.3.3. 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 the heavily grazed pasture. This reflects other studies that have reported greater loads of phosphorus from grazed than ungrazed areas and 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 (Thornton and Elledge, 2013, 2014) and over longer timeframes (Elledge and Thornton, 2017); 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.

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, 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, 2014) which greatly exceed the ranges given for forest in Bartley et al. (2012). Furthermore, soil phosphorus levels prior to land development at the Brigalow Catchment Study 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 (Thornton and Shrestha, 2021). 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).

4.4. Implications for the grazing industry

This study shows that grazing land management based on a safe long-term carrying capacity has a lower risk to water quality than heavily grazed pastures. This is essential knowledge for the grazing industry given the recent introduction of minimum practice agricultural standards for beef cattle grazing under the Reef protection regulation (Office of the Great Barrier Reef, 2020; The State of Queensland, 2020d). As per the regulation, where land has ground cover less than 50% at September 30 each year, measures must be undertaken to move land towards good (A) or fair (B) condition; that is, ground cover greater than 50%. This became enforceable under the Environmental Protection Act 1994 (The State of Queensland, 2020a) in December 2020 for the Burdekin region, and will commence in December 2021 for the Fitzroy region followed by the Wet Tropics, Mackay Whitsunday and Burnett Mary regions in December 2022. This is in addition to minimum standard record keeping requirements that commenced for most graziers in December 2019.

Adoption of a safe long-term carrying capacity can assist landholders to demonstrate compliance with this legislation. For example, the Grazing Water Quality Risk Framework shows that hillslope pasture management has seven performance indicators where each indicator is weighted based on its relative influence on water quality leaving farms (McCosker and Northey, 2015; The State of Queensland, 2020b). Hillslope management based on a safe long-term carrying capacity combined with seasonal forage budgeting to ensure pasture utilisation rates are not exceeded accounts for 45% of the relative influence. Ground cover monitoring and pasture management decisions to achieve ground cover thresholds account for a further 30% of the relative influence.

5. Conclusion

Long-term data from the Brigalow Catchment Study suggests that a stocking rate of 0.29 AE/ha/yr is a safe long-term carrying capacity for well-managed, rundown (30 to 40 years old) buffel grass pasture established on predominantly clay soils previously dominated by brigalow woodland. This recommendation is based on long-term pasture biomass and cattle live weight gains from the study site; however, stocking rates may need to be reduced at other locations unable to maintain similar amounts of pasture biomass under grazing (average 3500 kg/ha). Failure to reduce stocking rates on rundown pastures to match safe long-term carrying capacity led to increased hillslope 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, loads of total nitrogen and phosphorus both had substantial contributions of particulate and dissolved fractions. Although heavily grazed pasture had the highest runoff and greatest loads of total suspended solids and all nutrient parameters, it had the lowest EMCs. Heavy grazing pressure reduced ground cover which demonstrates the value of this indicator for assessing land condition. Continued monitoring would increase confidence in these findings by capturing more average and above average rainfall years, as wet years may produce different catchment responses. Continued monitoring to increase the dataset would enable statistical analyses of cover, hydrology and water quality interactions.

This study compliments other studies that have reported improved land condition and reduced economic risk by transitioning from heavy to conservative grazing pressures. Studies such as these underpin broader economic analyses that demonstrate long-term financial benefits for graziers who adopt improved management practices. This body of evidence demonstrates that reducing grazing pressure is a realistic economic option for landholders that will also have benefits for runoff water quality.

CRediT authorship contribution statement

C.M. Thornton: Conceptualization, Methodology, Investigation, Formal analysis, Writing – original draft, Writing – review & editing. **A. E. Elledge:** Conceptualization, Methodology, Investigation, Formal analysis, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This study was jointly funded by the Queensland Department of Resources (formerly the Department of Natural Resources, Mines and Energy) and the Australian and Queensland governments Paddock to Reef Integrated Monitoring, Modelling and Reporting program. The authors thank past and present staff from multiple Queensland Government agencies that have contributed to the long-term Brigalow Catchment Study, and Kevin Roots from the Department of Resources for the development of spatial datasets. We also thank our industry collaborator Elrose Brahman Stud, and in particular Walter and Leicha Gleeson from Brigalow Station for their assistance with on-ground cattle operations.

References

Ahern, C.R., P.G, S., Enderlin, N.G., Baker, D.E., 1994. The Soil Fertility of Central and North-East Queensland Grazing Lands. Department of Primary Industries, Queensland.

Alfaro, M., Salazar, F., Iraira, S., Teuber, N., Villarroel, D., Ramirez, L., 2008. Nitrogen, phosphorus and potassium losses in a grazing system with different stocking rates in a volcanic soil. Chil. J. Agric. Res. 68, 146–155.

Australian Bureau of Statistics, 2009. 4619.0 - Land management practices in the Great Barrier Reef catchments, preliminary 2008-09. www.abs.gov.au.

Bartley, R., Corfield, J.P., Abbott, B.N., Hawdon, A.A., Wilkinson, S.N., 2010. Impacts of improved grazing land management on sediment yields, part 1: hillslope processes. J. Hydrol. 389, 237–248.

Bartley, R., Corfield, J.P., Hawdon, A.A., Kinsey-Henderson, A.E., Abbott, B.N., Wilkinson, S.N., Keen, R.J., 2014. Can changes to pasture management reduce runoff and sediment loss to the Great Barrier Reef? The results of a 10-year study in the burdekin catchment, Australia. Rangel. J. 36, 67–84.

Bartley, R., Speirs, W.J., Ellis, T.W., Waters, D.K., 2012. A review of sediment and nutrient concentration data from Australia for use in catchment water quality models. Mar. Pollut. Bull. 65, 101–116.

Best, A., Zhang, L., McMahon, T., Western, A., Vertessy, R., 2003. A Critical Review of Paired Catchment Studies With Reference to Seasonal Flows and Climate Variability. Murray-Darling Basin Commission, Canberra.

Beutel, T.S., Trevithick, R., Scarth, P., Tindall, D., 2019. VegMachine.net. Online land cover analysis for the Australian rangelands. Rangel. J. 41, 355–362.

Biggs, A.J.W., Kidston, E.M., Searle, R.D., Wilson, P.L., Slater, B.K., Grundy, M.J., Heiner, I.J., Smith, C.D., Sweeney, C., 2000. In: Adams, J.A., Metherell, A.K. (Eds.), SALI: The Soil and Land Information system for Queensland, Proceedings of the Joint Australian and New Zealand Soil Science Conference. New Zealand Society of Soil Science, Canterbury, pp. 19–20.

Bowen, M.K., Chudleigh, F., 2017. Productivity and Profitability of a Range of Alternative Steer Growth Paths Resulting From Manipulating the Pasture Feed Base

in Central Queensland: A Modelling Approach. Department of Agriculture and Fisheries.
Brakenseik, D.L., Osborn, H.B., Rawls, W.J., 1979. Field manual for research in agricultural hydrology. In: Agriculture Handbook, 224. United States Department of Agriculture, Washington.
Butler, D.M., Ranells, N.N., Franklin, D.H., Poore, M.H., Green Jr., J.T., 2008. Runoff water quality from manured riparian grasslands with contrasting drainage and simulated grazing pressure. Agric. Ecosyst. Environ. 126, 250–260.
Butler, D.W., Fairfax, R.J., 2003. Buffel grass and fire in a gidgee and brigalow woodland: a case study from Central Queensland. Ecol. Manag. Restor. 4, 120–125.
Byrnes, R.C., Eastburn, D.J., Tate, K.W., Roche, L.M., 2018. A global meta-analysis of grazing impacts on soil health indicators. J. Environ. Qual. 47, 758–765.
Carter, J.O., Hall, W.B., Brook, K.D., McKeon, G.M., Day, K.A., Paull, C.J., 2000. In: Hammer, G.L., Nicholls, N., Mitchell, C. (Eds.), Applications of Seasonal Climate Forecasting in Agricultural and Natural Ecosystems. Springer, Dordrecht, Netherlands, pp. 329–349.
Cogger, H., Ford, H., Johnson, C., Holman, J., Butler, D.M., 2003. Impacts of Land Clearing on Australian Wildlife in Queensland. World Wide Fund for Nature Australia, Sydney.
Commonwealth of Australia, 1969. Aerial photography: baralaba, CAB0375. www.ga.gov.au/flight-diagrams/.
Cowie, B.A., Thornton, C.M., Radford, B.J., 2007. The brigalow catchment study: I. Overview of a 40-year study of the effects of land clearing in the brigalow bioregion of Australia. Aust. J. Soil Res. 45, 479–495.
Dalal, R.C., Thornton, C.M., Allen, D.E., Owen, J.S., Kopittke, P.M., 2021. Long-term land use change in Australia from native forest decreases all fractions of soil organic carbon, including resistant organic carbon, for cropping but not sown pasture. Agric. Ecosyst. Environ. 311, 1–11.
Daniel, J.A., Phillips, W.A., Northup, B.K., 2006. Influence of summer management practices of grazed wheat pastures on runoff, sediment, and nutrient losses. Trans. Am. Soc. Agric. Biol. Eng. 49, 349–355.
Duniway, M.C., Geiger, E.L., Minnick, T.J., Phillips, S.L., Belnap, J., 2018. Insights from long-term ungrazed and grazed watersheds in a salt desert Colorado plateau ecosystem. Rangel. Ecol. Manag. 71, 492–505.
Edwards, G., 2018. From Red to Green to Black: A Stewardship Incentives Scheme for Improving Queensland's Pastoral Lands. A Submission to The Royal Society of Queensland.
Eldridge, D.J., Poore, A.G.B., Ruiz-Colmenero, M., Letnic, M., Soliveres, S., 2016. Ecosystem structure, function, and composition in rangelands are negatively affected by livestock grazing. Ecol. Appl. 26, 1273–1283.
Elledge, A., 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. Agric. Ecosyst. Environ. 239, 119–131.
Environmental Systems Research Institute, 2020. ArcGIS, version 10.7.1. www.esri.com/en-us/arcgis.
Filet, P., Osten, D., 1996. Ecology of a grazed woodland: Keilambete grazing trial technical report 1994–1996. In: Project DAQ.090. Meat and Livestock Australia, Sydney.
Fitzroy Basin Association, 2018. VegMachine. https://vegmachine.net.
Gillingham, A.G., Gray, M.H., 2006. Measurement and modelling of runoff and phosphate movement from seasonally dry hill-country pastures. N. Z. J. Agric. Res. 49, 233–245.
Graham, T.W.G., Clark, R.A., Slater, B.K., Strachan, R.T., Rowland, P., 1991. Grazing Land Management in the Maranoa: Brigalow-Belah. Project Q091012. Queensland Department of Primary Industries, Brisbane.
Hawdon, A.A., Keen, R.J., Post, D.A., Wilkinson, S.N., 2008. Hydrological recovery of rangeland following cattle exclusion. In: Schmidt, J., Cochrane, T., Phillips, C., Elliott, S., Davies, T., Basher, L. (Eds.), Sediment Dynamics in Changing Environments, 325 ed. International Association of Hydrological Sciences, pp. 532–539.
Hay, V., Pittroff, W., Tooman, E.E., Meyer, D., 2006. Effectiveness of vegetative filter strips in attenuating nutrient and sediment runoff from irrigated pastures. J. Agric. Sci. 144, 349–360.
Hubbard, R.K., Newton, G.L., Hill, G.M., 2004. Water quality and the grazing animal. J. Anim. Sci. 82, E255–E263.
Isbell, R.F., 1996. The Australian Soil Classification. CSIRO Publishing, Collingwood, Victoria.
Jeffery, M., Loxton, I., 1998. In: Brigalow Research Station Technical Report 1997 to 1998. Report QI98078. Queensland Department of Primary Industries Queensland, p. 72.
Jeffery, M., Loxton, I., 1999. In: Brigalow Research Station Technical Report 1998 to 1999. Report QI98078. Queensland Department of Primary Industries, Queensland, p. 70.
Johnson, R.W., 1968. Brigalow clearing and the control of regrowth. Trop. Grasslands 2, 115–118.
Johnson, R.W., 2004. Vegetation survey of the Brigalow Research Station, Theodore, Queensland. In: Proc. R. Soc. Queensland, pp. 39–61.
Johnson, R.W., Back, P.V., 1974. Control of brigalow (Acacia harpophylla) regrowth by single and double ploughings. Queensland J. Agric. Anim. Sci. 31, 351–361.
Jones, P., Silcock, R., Scanlan, J., Moravek, T., 2016. Spelling strategies for recovery of pasture condition. In: Project B.NBP.0555. Meat and Livestock Australia, Sydney.
Koci, J., Sidle, R.C., Kinsey-Henderson, A.E., Bartley, R., Wilkinson, S.N., Hawdon, A.A., Jarihani, B., Roth, C.H., Hogarth, L., 2020. Effect of reduced grazing pressure on sediment and nutrient yields in savanna rangeland streams draining to the great barrier reef. J. Hydrol. 582.
Lai, L., Kumar, S., 2020. A global meta-analysis of livestock grazing impacts on soil properties. PLoS One 15, e0236638-e0236638.
Landsberg, R.G., Ash, A.J., Shepherd, R.K., Mckeon, G.M., 1998. Learning from history to survive in the future: management evolution on Trafalgar Station, north-East Queensland. Rangel. J. 20, 104–118.
Lawrence, D., French, V., 1992. Sown Pasture Management Notes: Western Downs and Maranoa. Queensland Department of Primary Industries.
Loxton, I., Anderson, E., Yule, D., Boadle, R., Logue, L., 1994. Brigalow Research Station Annual Report 1993. Report RQR94001. Queensland Department of Primary Industries, Queensland.
Loxton, I., Boadle, R., 1995. Brigalow Research Station Annual Report 1994. Report RQR95001. Queensland Department of Primary Industries, Queensland.
Loxton, I., Boadle, R., 1996. Brigalow Research Station Technical Report 1995. Report QI96074. Queensland Department of Primary Industries Queensland.
Loxton, I., Boadle, R., 1997. Brigalow Research Station Technical Report 1996. Report QI97057. Queensland Department of Primary Industries Queensland.
Loxton, I., Forster, S., 2000. Brigalow Research Station Technical Report 1999 to 2000. Report QI00098. Queensland Department of Primary Industries Queensland.
Mapfumo, E., Willms, W.D., Chanasyk, D.S., 2002. Water quality of surface runoff from grazed fescue grassland watersheds in Alberta. Water Qual. Res. J. Can. 37, 543–562.
McCloskey, G.L., Baheerathan, R., Dougall, C., Ellis, R., Bennett, F.R., Waters, D., Darr, S., Fentie, B., Hateley, L.R., Askildsen, M., 2021. Modelled estimates of fine sediment and particulate nutrients delivered from the great barrier reef catchments. Mar. Pollut. Bull. 165, 1–38.
McCosker, K., Northey, A., 2015. Paddock to reef: measuring the effectiveness of large scale investments in farm management change. Rural Ext. Innov. Syst. J. 11, 177–183.
McCosker, T., Winks, L., 1994. Phosphorus Nutrition of Beef Cattle in Northern Australia. Department of Primary Industries, Brisbane.
McDonald, S.E., Lawrence, R., Kendall, L., Rader, R., 2019. Ecological, biophysical and production effects of incorporating rest into grazing regimes: a global meta-analysis. J. Appl. Ecol. 56, 2723–2731.
McIvor, J.G., Williams, J., Gardener, C.J., 1995. Pasture management influences runoff and soil movement in the semi-arid tropics. Aust. J. Exp. Agric. 35, 55–65.
McKeon, G.M., Stone, G.S., Syktus, J.I., Carter, J.O., Flood, N.R., Ahrens, D.G., Bruget, D. N., Chilcott, C.R., Cobon, D.H., Cowley, R.A., Crimp, S.J., Fraser, G.W., Howden, S. M., Johnston, P.W., Ryan, J.G., Stokes, C.J., Day, K.A., 2009. Climate change impacts on northern Australian rangeland livestock carrying capacity: a review of issues. Rangel. J. 31, 1–29.
McLean, I., Blakeley, S., 2014. Adult equivalent methodology: a methodology to accurately and consistently calculate cattle grazing loads in northern Australia. In: Report to Meat and Livestock Australia. Bush AgriBusiness, Toowoomba, p. 33.
Meat and Livestock Australia, 2017a. Cattle numbers – as at June 2016 Natural Resource Management Region. www.mla.com.au.
Meat and Livestock Australia, 2017b. Market Information Services: Cattle Assessment Manual. Meat and Livestock Australia, Sydney.
Mein, R.G., Bieniaszewska-Hunter, H., Papworth, M., 1988. Land use changes and the hydrologic water balance. In: Stewarts Creek Experimental Area, Hydrology and Water Resources Symposium. Institution of Engineers Australia, Canberra.
Miller, J.J., Curtis, T., Chanasyk, D.S., Willms, W.D., 2017. Influence of cattle trails on runoff quantity and quality. J. Environ. Qual. 46, 348–355.
Minson, D.J., McDonald, C.K., 1987. Estimating forage intake from the growth of beef cattle. Trop. Grasslands 21, 116–122.
Moravek, T., Schrobback, P., East, M., Star, M., Rust, S., 2017. Understanding the economics of grazing management practices and systems for improving water quality run-off from grazing lands in the Burdekin and Fitzroy Catchments. In: Reef Plan Action 4: Gap Analysis Report 2016. Department of Agriculture and Fisheries.
Murphy, S.R., Larney, F.J., Willms, W.D., Demaere, P.R., Harden, S., 2008. Surface runoff response of native and introduced grasses under simulated rainfall in southern Alberta. Can. J. Soil Sci. 88, 337–348.
Nasser, M., 1986. In: A review of the Department of Primary Industries Brigalow Research Station 1963 to 1985. Report RQR 86002. Queensland Department of Primary Industries, Queensland, p. 42.
Nelson, P.N., Cotsaris, E., Oades, J.M., 1996. Nitrogen, phosphorus, and organic carbon in streams draining two grazed catchments. J. Environ. Qual. 25, 1221–1229.
Noble, A.D., Orr, D.M., Middleton, C.H., Rogers, L.G., 2000. Legumes in native pasture - asset or liability? A case history with stylo. Trop. Grasslands 34, 199–206.
O'Reagain, P., 2011. Wambiana Grazing Trial Extension: Testing and Developing Grazing Principles and Management Guidelines for the Seasonably Variable Tropical Savannas. Project B.NBP.0379. Meat and Livestock Australia, Sydney.
O'Reagain, P., Bainbridge, Z., Brodie, J., 2008. Wambiana Grazing Trial: Water Quality Update to Burdekin Dry Tropics NRM. ACTFR Report No. 08/24. Australian Centre for Tropical Freshwater Research, Townsville.
O'Reagain, P., Bushell, J., Holmes, B., 2011. Managing for rainfall variability: long-term profitability of different grazing strategies in a northern australian tropical savanna. Anim. Prod. Sci. 51, 210–224.
O'Reagain, P., Scanlan, J., Hunt, L., Cowley, R., Walsh, D., 2014. Sustainable grazing management for temporal and spatial variability in north Australian rangelands – a synthesis of the latest evidence and recommendations. Rangel. J. 36, 223–232.
Office of the Great Barrier Reef, 2020. Queensland reef water quality program: reef protection regulations. In: Farming in Reef Catchments. Grazing Guide (Agricultural Environmentally Relevant Activity Standard for Beef Cattle Grazing). The State of Queensland, Brisbane.
Owens, L.B., Edwards, W.M., Van Keuren, R.W., 1989. Sediment and nutrient losses from an unimproved, all-year grazed watershed. J. Environ. Qual. 18, 232–238.

Park, J.Y., Ale, S., Teague, W.R., 2017. Simulated water quality effects of alternate grazing management practices at the ranch and watershed scales. Ecol. Model. 360, 1–13.
Partridge, I.J., Burrows, B., Weston, E.J., 1994. Sown Pastures for the Brigalow Lands. Department of Primary Industries.
Paton, C., Hamilton, J., Emery, T., 2011. Best-Bet Practices for Managing the Grazing Lands of the Maranoa Balonne: A Technical Guide of Options for Optimising Animal Production, Profitability and Land Condition. Department of Employment, Economic Development and Innovation, Roma.
Peck, G., Buck, S., Hoffman, A., Holloway, C., Johnson, B., Lawrence, D., Paton, C., 2011. Review of productivity decline in sown grass pastures. In: Project B.NBP.0624. Meat and Livestock Australia, Sydney.
Peel, M.C., 2009. Hydrology: catchment vegetation and runoff. Prog. Phys. Geogr. 33, 837–844.
Polyakov, V.O., Nearing, M.A., Nichols, M.H., Scott, R.L., Stone, J.J., McClaran, M.P., 2010. Long-term runoff and sediment yields from small semiarid watersheds in southern Arizona. Water Resour. Res. 46, 1–12.
Potter, S.R., Andrews, S., Atwood, J.D., Kellogg, R.L., Lemunyon, J., Norfleet, L., Oman, D., 2006. Model Simulation of Soil Loss, Nutrient Loss, and Change in Soil Organic Carbon Associated With Crop Production. United States Department of Agriculture.
Queensland Department of Primary Industries, 1965. Brigalow Research Station. Queensland Department of Primary Industries, Queensland.
Queensland Department of Primary Industries, 1987. Brigalow Research Station Annual Report 1986 to 1987. Report RQR87013. Queensland Department of Primary Industries, Queensland, p. 53.
Queensland Department of Primary Industries, 1988. Brigalow Research Station Program Review 1988. Report RQR88017. Queensland Department of Primary Industries, Queensland, p. 71.
Queensland Department of Primary Industries, 1989. Brigalow Research Station Program Review 1989. Report RQR89011. Queensland Department of Primary Industries, Queensland, p. 74.
Queensland Department of Primary Industries, 1990. Brigalow Research Station Annual Report 1990. Report RQR90014. Queensland Department of Primary Industries, Queensland, p. 50.
Queensland Department of Primary Industries, 1991. Brigalow Research Station Annual Report 1991. Report RQR91003. Queensland Department of Primary Industries, Queensland, p. 67.
Queensland Department of Primary Industries, 1992. Brigalow Research Station Annual Report 1992. Report RQR92015. Queensland Department of Primary Industries, Queensland, p. 74.
Quinn, J.M., Stroud, M.J., 2002. Water quality and sediment and nutrient export from New Zealand hill-land catchments of contrasting land use. N. Z. J. Mar. Freshw. Res. 36, 409–429.
Radford, B.J., Thornton, C.M., 2011. Effects of 27 years of reduced tillage practices on soil properties and crop performance in the semi-arid subtropics of Australia. Int. J. Energy Environ. Econ. 19, 565–588.
Radford, B.J., Thornton, C.M., Cowie, B.A., Stephens, M.L., 2007. The brigalow catchment study: III. Productivity changes on brigalow land cleared for long-term cropping and for grazing. Aust. J. Soil Res. 45, 512–523.
Rickert, K.G., Stuth, J.W., McKeon, G.M., 't Mannetje, L., 2000. Modelling pasture and animal production. In: Jones, R.M. (Ed.), Field and Laboratory Methods for Grassland and Animal Production Research. CABI Publishing, New York, pp. 29–66.
Robertson, F.A., Nash, D.M., 2008. Phosphorus and nitrogen in soil, plants, and overland flow from sheep-grazed pastures fertilized with different rates of superphosphate. Agric. Ecosyst. Environ. 126, 195–208.
Rolfe, J., Star, M., Curcio, A., 2020. Can extension programs improve grazing management in rangelands: a case study in Australia's great barrier reef catchments. Rangel. J. 42, 447–459.
Roots, K., 2016. Land area under various soil orders extracted for grazing in the Fitzroy Basin using layers sourced from the Queensland Government's Spatial Information Resource (SIR) database: "SLR.ASRIS_ASR_L4_2M_RESULTS_V" Australian Soil Resource Information System (ASRIS) Level 4 (1:2,000,000 scale) Australian Soil Classifications replaced with sections of "SLR.ASRIS_ASR_L5_250K_RESULTS_V" Level 5 (1:250,000 scale) where available; "RSC.QLD_LANDUSE_CURRENT_X" land use map which is a product of the Queensland Land Use Mapping Program (QLUMP)"; and "P2R_56_sub_basins" shapefile provided by C. Dougall (Paddock to Reef modeller, Department of Natural Resources and Mines) dissolved to the Fitzroy Basin using "PROP.QLD_NRMREGBDY_100K" natural resource management boundaries. Developed using ArcGIS version 10.3. Department of Natural Resources and Mines, Rockhampton.
Roth, C.H., 2004. A framework relating soil surface condition to infiltration and sediment and nutrient mobilization in control rangelands of northeastern Queensland, Australia. Earth Surf. Process. Landf. 29, 1093–1104.
Schepers, J.S., Francis, D.D., 1982. Chemical water quality of runoff from grazing land in Nebraska: I. Influence of grazing livestock. J. Environ. Qual. 11, 351–354.
Schepers, J.S., Hackes, B.L., Francis, D.D., 1982. Chemical water quality of runoff from grazing land in Nebraska: II. Contributing factors. J. Environ. Qual. 11, 355–359.
Schwarte, K.A., Russell, J.R., Kovar, J.L., Morrical, D.G., Ensley, S.M., Yoon, K.J., Cornick, N.A., Cho, Y.I., 2011. Grazing management effects on sediment, phosphorus, and pathogen loading of streams in cool-season grass pastures. J. Environ. Qual. 40, 1303–1313.
Silburn, D.M., Carroll, C., Ciesiolka, C.A.A., de Voil, R.C., Burger, P., 2011. Hillslope runoff and erosion on duplex soils in grazing lands in semi-arid Central Queensland. I. Influences of cover, slope, and soil. Soil Res. 49, 105–117.
Silburn, D.M., Cowie, B.A., Thornton, C.M., 2009. The brigalow catchment study revisited: effects of land development on deep drainage determined from non-steady chloride profiles. J. Hydrol. 373, 487–498.
Silcock, R.G., Jones, P., Hall, T.J., Waters, D.K., 2005. Enhancing Pasture Stability and Profitability for Producers in Poplar Box and Silver-leaved Ironbark Woodlands. Project NAP3.208. Meat and Livestock Australia, Sydney.
Sinclair, S., White, D., 2004. In: Brigalow Research Station Technical Report July 2001 to December 2003. Report QO04013. Queensland Department of Primary Industries and Fisheries, Queensland, p. 93.
Sirimarco, X., Barral, M.P., Villarino, S.H., Laterra, P., 2018. Water regulation by grasslands: a global meta-analysis. Ecohydrology 11, e1934.
Spiegel, N., 2016. Developing an RD&E Project to Address Loss of Productivity in Queensland Pastures Invaded by Indian Couch (Bothriochloa pertusa).
Stockwell, T.G.H., Smith, P.C., Stafford Smtih, D.M., Hirst, D.J., 1991. Sustaining productive pastures in the tropics 9. Managing cattle. Trop. Grasslands 25, 137–144.
Strachan, R.T., 1976. Beef cattle production. Queensland Agric. J. 102, 178–183.
Stringer, T.L., 1976. In: A Review of the Department of Primary Industries Brigalow Research Station. Queensland Department of Primary Industries, Queensland, p. 20.
Terrestrial Ecosystem Research Network, 2010. Seasonal ground cover. http://data.auscover.org.au/xwiki/bin/view/Product_pages/Seasonal_Ground_Cover.
The State of Queensland, 1965. Aerial photography: roundstone, QAP1569. https://qimagery.information.qld.gov.au/.
The State of Queensland, 1977. Aerial photography: Moura, QAP3379. https://qimagery.information.qld.gov.au/.
The State of Queensland, 1984. Aerial photography: Moura, QAP4293. https://qimagery.information.qld.gov.au/.
The State of Queensland, 1991. Aerial photography: Moura, QAP4979. https://qimagery.information.qld.gov.au/.
The State of Queensland, 2018. Reef 2050 Water Quality Improvement Plan 2017-2022. Reef Water Quality Protection Plan Secretariat.
The State of Queensland, 2019. Regional Ecosystem Description Database (REDD), version 11.1. https://environment.ehp.qld.gov.au/regional-ecosystems/.
The State of Queensland, 2020a. Environmental protection act 1994. www.legislation.qld.gov.au.
The State of Queensland, 2020b. Management practices: grazing water quality risk framework 2017–2022. www.reefplan.qld.gov.au.
The State of Queensland, 2020c. Queensland spatial catalogue: QSpatial. http://qldspatial.information.qld.gov.au.
The State of Queensland, 2020d. Reef protection regulations. For producers. Retrieved 17 March 2021 from. In: Grazing. www.qld.gov.au/environment/agriculture/sustainable-farming/reef/reef-regulations/producers/grazing.
The State of Queensland, 2020e. Regional ecosystem. www.qld.gov.au/environment/plants-animals/plants/ecosystems.
The State of Queensland, 2021. Forage. www.longpaddock.qld.gov.au/forage/.
Thornton, C., Elledge, A., 2016. Tebuthiuron movement via leaching and runoff from grazed vertisol and alfisol soils in the Brigalow Belt bioregion of Central Queensland, Australia. J. Agric. Food Chem. 64, 3949–3959.
Thornton, C., Elledge, A., Shrestha, K., Wallace, S., Bosomworth, B., 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. In: International Interdisciplinary Conference on Land Use and Water Quality: Effect of Agriculture on the Environment, The Hague, Netherlands.
Thornton, C.M., Cowie, B.A., Freebairn, D.M., Playford, C.L., 2007. The brigalow catchment study: II. Clearing brigalow (Acacia harpophylla) for cropping or pasture increases runoff. Aust. J. Soil Res. 45, 496–511.
Thornton, C.M., Elledge, A.E., 2013. Runoff nitrogen, phosphorus and sediment generation rates from pasture legumes: an enhancement to reef catchment modelling (Project RRRD009). In: Report to the Reef Rescue Water Quality Research and Development Program. Reef and Rainforest Research Centre Limited, Cairns, p. 85.
Thornton, C.M., Elledge, A.E., 2014. Runoff nitrogen, phosphorus and sediment generation rates from pasture legumes: addendum to paddock scale water quality monitoring for 2013 and 2014 (Project RRRD009). In: Report to the Reef Rescue Water Quality Research and Development Program. Reef and Rainforest Research Centre Limited, Cairns, p. 13.
Thornton, C.M., Elledge, A.E., 2018. In: Currie, L.D., Christensen, C.L. (Eds.), 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. Occasional Report No. 31, Farm Environmental Planning – Science, Policy and Practice. Fertilizer and Lime Research Centre, Massey University, Palmerston North New Zealand, pp. 1–8.
Thornton, C.M., Shrestha, K., 2021. The brigalow catchment study: V. Clearing and burning brigalow (Acacia harpophylla) in Queensland, Australia, temporarily increases surface soil fertility prior to nutrient decline under cropping or grazing. Soil Res. 59, 146–169.
Thornton, C.M., Yu, B., 2016. The brigalow catchment study: IV. Clearing brigalow (Acacia harpophylla) for cropping or grazing increases peak runoff rate. Soil Res. 54, 749–759.
Tothill, J.C., Hargreaves, J.N.G., Jones, R.M., 1978. BOTANAL - A comprehensive sampling and computing procedure for estimating pasture yield and composition. In: 1. Field Sampling. CSIRO Tropical Agronomy Technical Memorandum No. 8, pp. 1–20.
Trevithick, B., 2017. Seasonal cover deciles - Landsat, JRSRP algorithm, Australia coverage. Retrieved 05 June 2018 from. http://data.auscover.org.au.

Tulloch, A.I.T., Barnes, M.D., Ringma, J., Fuller, R.A., Watson, J.E.M., 2016. Understanding the importance of small patches of habitat for conservation. J. Appl. Ecol. 53, 418–429.
Udawatta, R.P., Henderson, G.S., Jones, J.R., Hammer, D.H., 2011. Phosphorus and nitrogen losses in relation to forest, pasture and row-crop land use and precipitation distribution in the Midwest. Rev. Sci. Eau 24, 269–281.
Vadas, P.A., Aarons, S.R., Butler, D.M., Dougherty, W.J., 2011. A new model for dung decomposition and phosphorus transformations and loss in runoff. Soil Res. 49, 367–375.
Van Kessel, C., Clough, T., van Groenigen, J.W., 2009. Dissolved organic nitrogen: an overlooked pathway of nitrogen loss from agricultural systems? J. Environ. Qual. 38, 393–401.
van Oudenhoven, A.P.E., Veerkamp, C.J., Alkemade, R., Leemans, R., 2015. Effects of different management regimes on soil erosion and surface runoff in semi-arid to sub-humid rangelands. J. Arid Environ. 121, 100–111.
Vink, S., Ford, P.W., Bormans, M., Kelly, C., Turley, C., 2007. Contrasting nutrient exports from a forested and an agricultural catchment in South-Eastern Australia. Biogeochemistry 84, 247–264.
Wachendorf, C., Taube, F., Wachendorf, M., 2005. Nitrogen leaching from 15N labelled cow urine and dung applied to grassland on a sandy soil. Nutr. Cycl. Agroecosyst. 73, 89–100.
Walsh, D., Cowley, R.A., 2011. Looking back in time: can safe pasture utilisation rates be determined using commercial paddock data in the Northern Territory? Rangel. J. 33, 131–142.
Wang, C., Tang, Y., 2019. A global meta-analyses of the response of multi-taxa diversity to grazing intensity in grasslands. Environ. Res. Lett. 14, 114003.
Waterhouse, J., Henry, N., Mitchell, C., Smith, R., Thomson, B., Carruthers, C., Bennett, B., Brodie, J., McCosker, K., Northey, A., Poggio, M.J., Moravek, T., Gordon, B., Orr, G., Silburn, M., Shaw, M., Bickle, M., Ronan, M., Turner, R., Waters, D., Tindall, D., Trevithick, R., Ryan, T., VanderGragt, M., Houlden, B., Robillot, C., 2018. Paddock to Reef Integrated Monitoring, Modelling and Reproting Program: Program Design 2018-2022. Report to Office of the Great Barrier Reef. C2O Consulting, Townsville.
Waterhouse, J., Schaffelke, B., Bartley, R., Eberhard, R., Brodie, J., Star, M., Thorburn, P., Rolfe, J., Ronan, M., Taylor, B., Kroon, F., 2017. Scientific Consensus Statement: Land Use Impacts on Great Barrier Reef Water Quality and Ecosystem Condition.
Webb, A.A., 1971. Soil Survey of Brigalow Research Station. Queensland Department of Primary Industries, Brisbane.
Webb, A.A., Dowling, A.J., Nugent, P.J., 1982. Studies on solodic soils under Acacia harpophylla-Eucalyptus cambageana forests in Central Queensland 1. Chemical characteristics. Queensland J. Agric. Anim. Sci. 39, 109–123.
Webb, A.A., Maltby, J.E., Gill, J.Y., Nugent, P.J., 1977. Chemical Properties and Fertility Status of Soils of the Brigalow Research Station, Central Queensland. Queensland Department of Primary Industries, Brisbane.
Xu, S., Jagadamma, S., Rowntree, J., 2018. Response of grazing land soil health to management strategies: a summary review. Sustainability 10, 4769.
Yule, D.F., 1989. Introduction. In: Lawrence, P.A., Thorburn, P.J. (Eds.), Changes in Hydrology, Soil Fertility and Productivity of Brigalow Catchments Following Clearing. Queensland Department of Primary Industries.