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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

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ABSTRACT

Native vegetation has been extensively cleared for agricultural systems worldwide, resulting in increased pollutant loads that often have adverse impacts downstream. This study uses 25 years of flow data and 10 years of sediment, nitrogen and phosphorus (total and dissolved) event mean concentrations from paired catchments to quantify the effect of changing land use from virgin brigalow (*Acacia harpophylla*) woodland in a semi-arid subtropical region of Australia into an unfertilised crop or conservatively grazed pasture system. Both the cropped and grazed catchments exported higher loads of sediment and phosphorus than the virgin brigalow catchment; however, the grazed catchment exported less total, oxidised and dissolved nitrogen than the virgin brigalow catchment. The cropped catchment exported higher loads of all water quality parameters compared to the grazed catchment. The simple hydrology and water quality model presented was effective for measuring the effect of land use change on runoff water quality. Variations in water quality between the three catchments are likely due to the presence of native legumes, ground cover, tillage practices and pasture rundown.

1. Introduction

Worldwide, the total area of forests in 2010 was estimated to be four billion hectares, or 31% of the total land area (Food and Agriculture Organization of the United Nations, 2010). Deforestation is typically associated with natural causes, such as fire and drought, and change of land use to agriculture. However, rates of net gain and loss vary between country and agro-ecological zones (Food and Agriculture Organization of the United Nations, 2010). For example, in Australia the Fitzroy Basin Land Development Scheme commenced in 1963 resulting in 4.5 Mha of virgin brigalow woodland being cleared for agriculture. This scheme continued through to the 1990s (Department of Lands, 1968; Partridge et al., 1994), with broad-scale clearing in Queensland only ceasing in 2006 (Thornton et al., 2012). In 2009, 74.8% (11.7 Mha) of the Fitzroy Basin was being used for agricultural purposes, with 71.5% grazed and 3.2% cropped (Australian Bureau of Statistics, 2009).

Pollutant loads exported in runoff have increased from natural rates as a consequence of broad-scale clearing of native vegetation and subsequent change of land use to agriculture. For example, Kroon et al. (2012) estimated that since European settlement mean annual loads exported from six catchments along the coast of Queensland, Australia, into the Great Barrier Reef have increased 5.5 times for total suspended sediment (17,000 kt yr^{-1}), 5.7 times for total nitrogen (80,000 t yr^{-1}) and 8.9 times for total phosphorus (16,000 t yr^{-1}). Transport of sediment and nutrients from the landscape into the Great Barrier Reef causes increased eutrophication and turbidity (Brodie et al., 2011; Hansen et al., 2002), which can lead to crown-of-thorns starfish (*Acanthaster planci*) outbreaks and coral mortality (Brodie and Waterhouse, 2012; De'ath et al., 2012). The impact of different agricultural activities on downstream water quality is an issue in common with other parts of Australia and the world (Barlow et al., 2007; Bossa et al., 2012; Brion et al., 2011; Dilshad et al., 1996; Jarvie et al., 2010; Lal, 1996; Singh and Mishra, 2014; Vink et al., 2007).

It is well documented that runoff volume and/or sediment load increase when native forest is cleared for agriculture (Cowie et al., 2007; Hunter and Walton, 2008; Siriwardena et al., 2006; Thornton et al., 2007). Numerous studies have also demonstrated higher runoff volume and/or sediment loads from cropped than grazed areas (Freebairn et al., 2009; Murphy et al., 2013; Stevens et al.,

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2006; Wilson et al., 2014). However, studies that have reported nutrient loads from agricultural systems tend to focus on total loads rather than dissolved loads (O'Reagain et al., 2005; Povilaitis et al., 2014; Stevens et al., 2006; Wilson et al., 2014). Dissolved nutrients pose a great risk to aquatic systems, as they are less likely to settle than nutrients bound to sediment (Silburn et al., 2007). For example, Devlin and Brodie (2005) mapped flood plumes from rivers exporting into the Great Barrier Reef over nine years and found that most suspended solids and associated particulate nutrients were deposited within 10 km of the river mouth while dissolved nutrients were transported with the plume 50–200 km from the river mouth.

Studies that have reported both total and dissolved nutrients are typically at the catchment scale (Joo et al., 2012; Li et al., 2014; Packett et al., 2009), but catchments often have multiple land uses within the monitored area so it is difficult to separate the impacts of each land use on water quality (Bartley et al., 2012; Li et al., 2014; Povilaitis et al., 2014). Bartley et al. (2012) reviewed 755 sediment, nitrogen and phosphorus data points from studies across Australia for use in catchment scale water quality models. They found that a catchment with less than 90% of a specific land use could have its water quality signature influenced by the other land uses, whereas a catchment dominated by a single land use (>90%) was a more appropriate representation of that specific land use. However, using data from sites with more than 90% of the area dominated by a single land use dramatically reduced the number of data points and also biased data towards smaller plot sizes for intensive land uses, such as sugar cane, which rarely cover large areas of a catchment (Bartley et al., 2012). Thus, there is currently a paucity of total and dissolved water quality data from areas greater than plot scale that are dominated by a single land use.

This study investigates the impact of changing land use from a virgin brigalow woodland into a crop or pasture system on runoff water quality. It models data based on a 17 year calibration period of three catchments in their virgin condition before changing the land use of two catchments to agriculture, and subsequent monitoring of all three catchments to collect 25 years flow and 10 years water quality data. The model presented uses long-term event mean concentrations (EMCs) with a regression based flow model described by Thornton et al. (2007). This research is unique as it: 1) reports on total and dissolved nitrogen and phosphorus in addition to sediment; and 2) compares both cropped and grazed catchments with a virgin woodland control catchment. This study improves understanding on the impact of agriculture on runoff water quality relative to the pre-European landscape and provides a comparison of water quality from crop and pasture systems.

2. Methods

2.1. Site description

The Brigalow Catchment Study (24°48′S and 149°47′E) is a paired, calibrated catchment study located near Theodore in central Queensland, Australia (Fig. 1). It was established in 1965 to quantify the impact of land development for agriculture on hydrology, productivity and resource condition (Cowie et al., 2007). The study site was selected to represent the Brigalow Belt Bioregion which covers an area approximately 36.7 Mha from Townsville in north Queensland to Dubbo in central-western New South Wales (Thornton et al., 2007). The site in its native state was dominated by brigalow (*Acacia harpophylla*) trees, either in a monoculture or in association with other species, such as belah (*Casuarina cristata*) and Dawson River blackbutt (*Eucalyptus cambageana*) (Johnson, 2004). The extant uncleared vegetation at the Brigalow Catchment Study is classified as regional ecosystems 11.4.8, woodland to open forest dominated by *Eucalyptus cambageana* and *Acacia harpophylla*, and 11.4.9, open forest and occasionally woodland dominated by *Acacia harpophylla* (Queensland Government, 2014). Slope of the land averages 2.5% (range from 1.8 to 3.5%) and soils are an association of black and grey Vertosols, black and grey Dermosols, and black and brown Sodosols. Vertosols and Dermosols (clay soils) cover approximately 70% of Catchments 1 and 2, and 58% of Catchment 3; Sodosols cover the remaining area (Cowie et al., 2007). These soil types are representative of 67% of the Fitzroy Basin under grazing: 28% Vertosols, 28% Sodosols and 11.3% Dermosols (Roots, 2016). The region has a semi-arid, subtropical climate and mean annual hydrological year (October 1965 to September 2014) rainfall at the site was 661 mm.

2.2. Calibration and development of catchments

Three contiguous catchments were monitored for rainfall and runoff from 1965 to 1982 (17 years). Each catchment was instrumented to measure runoff using a 1.2 m steel HL flume with a 3.9×6.1 m concrete approach box. Water heights through the flumes were recorded using mechanical float recorders and converted to discharge using a rating table. Rainfall was recorded adjacent to each flume and at the top of the catchments using a tipping bucket rain gauge (Thornton et al., 2007). A runoff event was defined as commencing when stage height exceeded zero and finished when it returned to zero. These data were used to derive mathematical relationships to predict runoff from Catchment 2 (C2) and Catchment 3 (C3) given known runoff from Catchment 1 (C1) (Thornton et al., 2007). During this period, it was found that C2 and C3 in their uncleared state had 95% and 72% of the runoff from C1, respectively. Each catchment had its own intrinsic hydrological signature; for example, C3 had more runoff events but less total runoff volume on an annual basis compared to C1 and C2. Nonetheless, approximately 5% of the mean annual rainfall become runoff in all three catchments (Thornton et al., 2007).

Land development occurred between 1982 and 1983; that is, C1 remained virgin brigalow woodland to provide an uncleared control treatment, while C2 and C3 were cleared using a chain dragged between two dozers and the fallen timber burnt in-situ (Cowie et al., 2007). C2 was then developed for cropping with the construction of contour banks and grassed waterways, while C3 was developed for grazing by the planting of improved buffel grass pasture (Fig. 2).

2.3. Land use comparisons

Rainfall and runoff were monitored from the virgin brigalow woodland (C1), cropped (C2) and grazed (C3) catchments from 1984 until 2010 (Thornton and Elledge, 2013). This equates to 25 full hydrological years (October to September) monitoring and two incomplete hydrological years; July 1984 to September 1984, and October 2009 to January 2010. Over the 25 years, C2 had one sorghum crop followed by nine monoculture wheat crops, and then was opportunity cropped with sorghum (*Sorghum bicolor*), wheat (*Triticum* spp.), barley (*Hordeum vulgare*) or chick peas (*Cicer arietinum*). Zero or reduced till fallows were introduced in 1990. There were no fertiliser inputs in the cropped catchment (Radford et al., 2007). C3 was grazed at industry recommended stocking rates with utilisation to result in no less than 1000 kg ha^{-1} of pasture available at any time. Conservative management of this catchment has resulted in groundcover averaging 91% since 2000 (earlier data not available), which is greater than paddocks of the same land type within a 50 km radius which averaged only 74% (Fitzroy Basin Association, 2016). The foliage projective cover of tree regrowth in C3 has remained below 15% (Department of Science, Information Technology and Innovation, 2016). There was

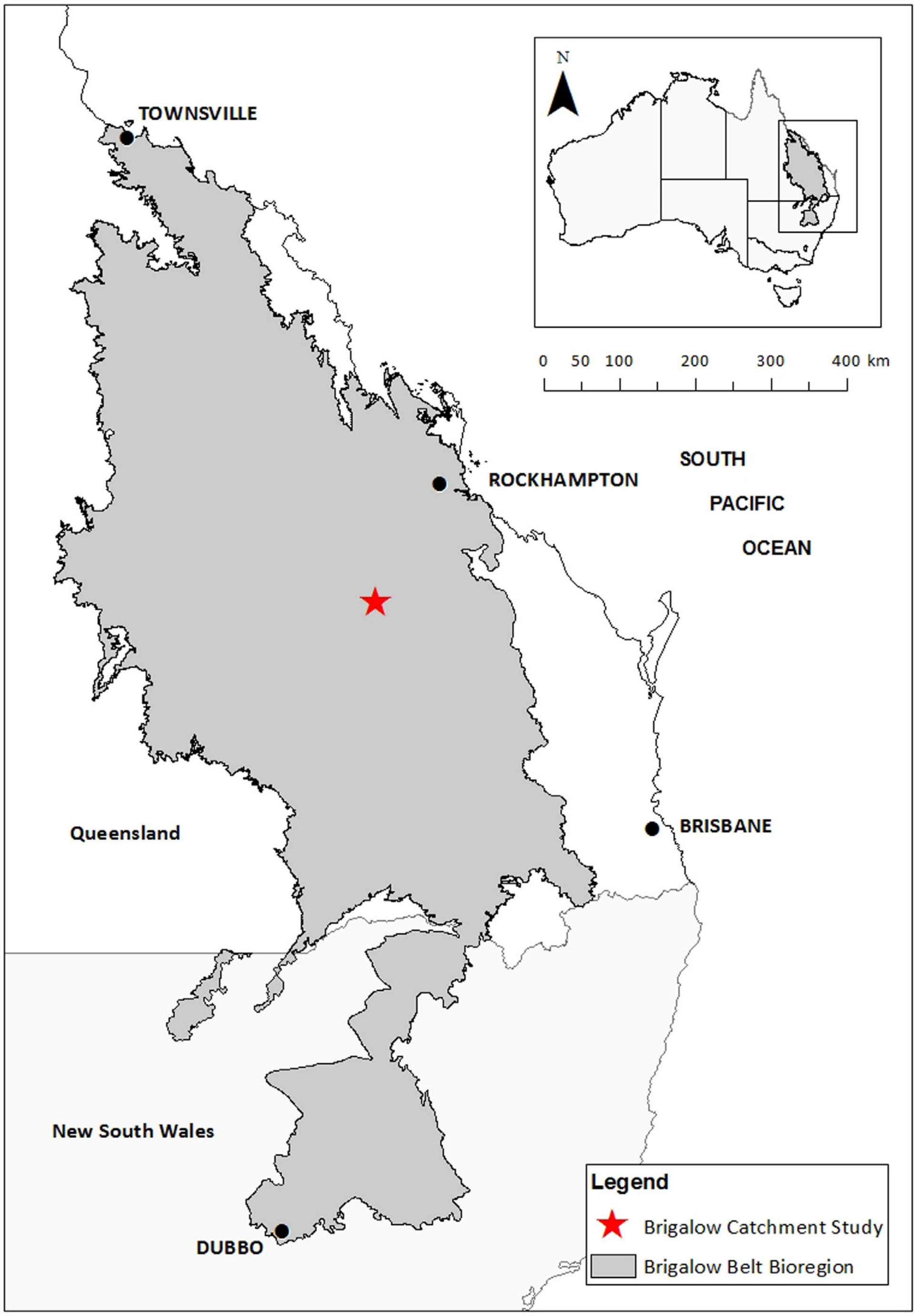

Fig. 1. Location of the Brigalow Catchment Study within the Brigalow Belt Bioregion of central Queensland, Australia.

no fertiliser inputs or supplement feeding in the pasture catchment (Radford et al., 2007).

Discrete water quality samples were obtained using auto-samplers from 2000 to 2010. Auto-samplers were programmed to sample every 0.1 m change in absolute stage height. Runoff samples were analysed for seven parameters by Queensland Health Forensic and Scientific Services (https://www.health.qld.gov.au/qhcss/qhss/) (Table 1).

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 loads over all the 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. Where samples were only collected on the rising limb of the hydrograph, the event peak was considered to be the end of the sampling interval for the last discrete sample, and the mean concentration of the discrete samples was applied to flow from the event peak to the event end. Event based EMCs were calculated by dividing total event load by total event flow.

Mean annual EMC was calculated by averaging the event based EMCs. These values were then averaged to determine the long-term EMC for each catchment. Where missing flow data occurred, estimations were obtained using the “HowLeaky?” modelling approach of Thornton et al. (2007). Where missing water quality data occurred, estimations were obtained by multiplying the long-

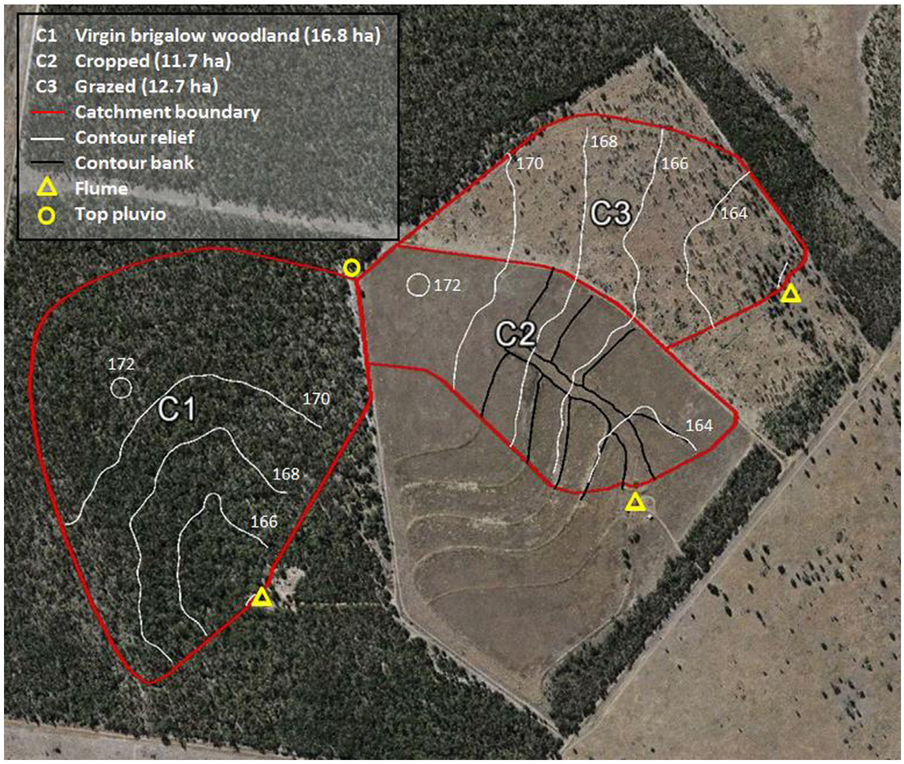

Fig. 2. Aerial photo of the three catchments monitored at the Brigalow Catchment Study following land use change of two catchments from virgin brigalow woodland to crop and pasture systems.

term EMC by the observed flow. Mean annual load was calculated by dividing the cumulative observed load for each catchment by the number of full hydrological years monitoring data (n = 25). The effect of changing land use from virgin brigalow woodland to crop or pasture systems on sediment, nitrogen and phosphorus loads (kg ha^{-1}) on an event basis were calculated by: (Table 2)

$$\left(\frac{(Q_{Obs} \times EMC_{Current}) - (Q_{Est} \times EMC_{Brigalow})}{1,000,000}\right) \div Area$$

Observed load was calculated by multiplying the observed event flow from 1984 to 2010 by the long-term EMC (2000 to 2010) for the respective catchment. Predicted load was calculated by multiplying the estimated flow of C2 and C3 had they remained virgin brigalow woodland (using the relationship of flow between the catchments during the calibration phase from 1965 to 1982; for example, C2 in an uncleared state had 95% of the runoff from C1) by the EMC for the virgin brigalow catchment. Mean annual land use change effect was calculated by dividing the cumulative difference in observed and predicted loads by the number of full hydrological years of monitoring data (n = 25). The assumptions of this approach are that water quality from the three catchments in their virgin state would have been similar, and that the long-term EMC values for C1 apply to all catchments had they remained virgin brigalow woodland.

3. Results

3.1. Hydrology

Total annual rainfall exceeded the long-term mean annual rainfall of 661 mm for the Brigalow Catchment Study in 10 out of the 25 full hydrological years monitored (Fig. 3). Observed mean annual runoff from the cropped and grazed catchments were 2.48 times (65.8 mm) and 1.97 times (52.2 mm) greater than observed runoff from the virgin brigalow woodland (26.5 mm), respectively. Similarly, observed runoff from the cropped catchment was 2.60 times greater than predicted runoff from this catchment had it remained uncleared (25.3 mm), and observed runoff from the

Table 1
Methods used by Queensland Health Forensic and Scientific Services for sediment, nitrogen and phosphorus analyses of water samples.

Parameter	Method
Total Suspended Solids	Method 18211 based on gravimetric quantification of solids in water.
Total Nitrogen	Method 13802 by simultaneous persulfate digestion. For the period 2000 to 2003, method 13804 based on simultaneous Kjeldahl digestion was reported and total nitrogen was manually calculated as total Kjeldahl nitrogen + oxidised nitrogen.
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.
Dissolved Inorganic Nitrogen	Manually calculated as oxidised nitrogen + ammonium nitrogen.
Total Phosphorus	Method 13800 by simultaneous persulfate or Kjeldahl digestion.
Dissolved Inorganic Phosphorus	Method 13799 by flow injection analysis; also known as orthophosphate.

Table 2
Model parameters were defined as follows.

Parameter		Description
Q_{Obs}	=	Observed discharge from the catchment under current land use (L event^{-1})
$EMC_{Current}$	=	Observed long-term event mean concentration from the catchment under current land use (mg L^{-1})
Q_{Est}	=	Estimated discharge from the catchment had it remained virgin brigalow woodland (L event^{-1}) (Thornton et al., 2007)
$EMC_{Brigalow}$	=	Observed long-term event mean concentration from the virgin brigalow catchment (mg L^{-1})
Area	=	Catchment area (ha)

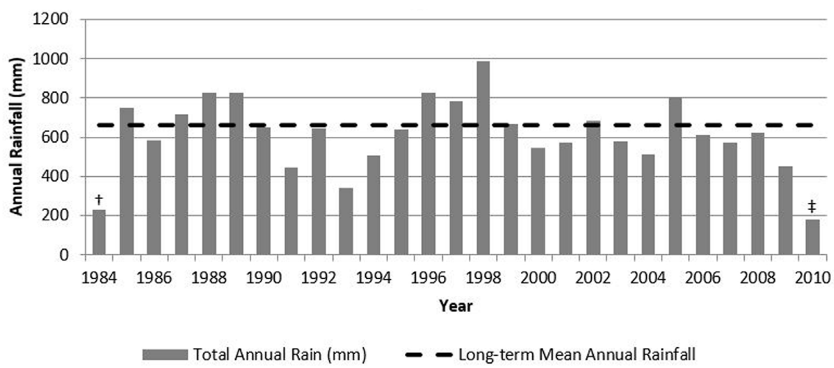

Fig. 3. Total annual hydrological year rainfall (mm) for 1984 to 2010 relative to the long-term mean annual rainfall for the Brigalow Catchment Study. † Total rainfall only from 25/07/1984, as this relates to the first runoff event recorded at the Brigalow Catchment Study following land development. ‡ Total rainfall only to 19/01/2015, as event data after this date was excluded from the presented model due to a change in management practices.

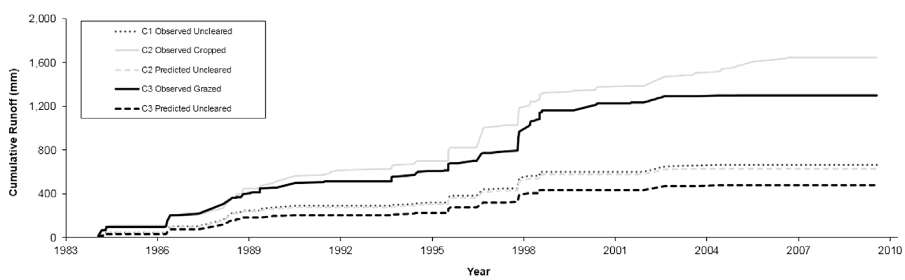

Fig. 4. Cumulative runoff (mm) from the virgin brigalow woodland (C1), crop (C2) and pasture (C3) catchments, and predicted runoff for the cropped and grazed catchments had they remained virgin brigalow woodland. Data for the period July 1984 to January 2010; however, no events occurred between March 2007 and January 2010.

grazed catchment was 2.74 times greater than predicted runoff from this catchment had it remained uncleared (19.0 mm). The rate of increase in cumulative runoff was greater in years with above average rainfall, particularly from 1987 to 1989 and 1996 to 1999 (Fig. 4). Over the 25 year period, the virgin brigalow catchment discharged a total of 663 mm runoff over 45 days, the cropped catchment discharged a total of 1647 mm runoff over 99 days, and the grazed catchment discharged a total of 1304 mm runoff over 80 days.

Table 3
Long-term event mean concentrations (mg L^{-1}) of sediment, nitrogen and phosphorus for the virgin brigalow woodland, cropped and grazed pasture catchments over 10 years (2000–2010).

Parameter	Event Mean Concentration (mg L^{-1})		
	Woodland (C1)	Crop (C2)	Pasture (C3)
Total Suspended Solids	307	798	229
Total Nitrogen	9.85	5.37	2.17
Oxidised Nitrogen	6.27	2.17	0.07
Ammonium Nitrogen	0.06	0.11	0.04
Dissolved Inorganic Nitrogen	6.32	2.27	0.11
Total Phosphorus	0.32	0.93	0.41
Dissolved Inorganic Phosphorus	0.12	0.35	0.22

3.2. Event mean concentrations

Long-term EMCs for the three monitored catchments from 2000 to 2010 are presented in Table 3. Concentrations of total, oxidised and dissolved inorganic nitrogen from virgin brigalow woodland were 1.83, 2.89 and 2.78 times greater than concentrations from the cropped catchment and 4.53, 95.10 and 59.89 times greater than concentrations from the grazed catchment, respectively. In contrast, concentrations of total suspended solids, total and dissolved inorganic phosphorus, and ammonium nitrogen from the cropped catchment were 2.60, 2.90, 3.00 and 1.73 times greater than concentrations from the virgin brigalow catchment and 3.49, 2.26, 1.57 and 2.67 times greater than concentrations from the grazed catchment, respectively.

Overall, the proportion of dissolved inorganic phosphorus that comprised total phosphorus was 37% from the virgin brigalow catchment, 38% from the cropped catchment and 55% from the grazed catchment. The proportion of ammonium nitrogen that comprised dissolved inorganic nitrogen was 1% from the virgin brigalow catchment, 5% from the cropped catchment and 38% from the grazed catchment.

3.3. Sediment, nitrogen and phosphorus loads

Cumulative loads of sediment, nitrogen and phosphorus are presented in Figs. 5–11. Similar to runoff, the rate of increase in cumulative loads was greater in years with above average rainfall, particularly from 1987 to 1989 and 1996 to 1999.

The cropped catchment exported more sediment and nutrients (total and dissolved) than the grazed catchment over the 25 year period (Table 4). Changing land use from virgin brigalow woodland to either agricultural system increased loads of total suspended solids, total and dissolved inorganic phosphorus, and ammonium nitrogen; the cropped catchment exported 6.45, 7.21, 7.45 and 4.29 times greater loads and the pasture catchment exported 1.46, 2.53, 3.75 and 1.27 times greater loads, respectively. In contrast, loads of oxidised and dissolved inorganic nitrogen were higher from virgin brigalow woodland than both agricultural systems; 1.16 and 1.12 times greater than loads from the cropped catchment and 48.34 and 30.44 times greater than loads from the grazed catchment, respectively. The virgin brigalow and cropped catchments exported 2.30 and 3.12 times greater total nitrogen than the pasture catchment, respectively.

Observed mean annual loads of total suspended solids, total phosphorus and dissolved inorganic phosphorus from the cropped catchment were 6.88, 7.70 and 7.95 times greater, respectively, than predictions from this catchment had it remained uncleared (Table 4). Total and ammonium nitrogen were also 1.42 and 4.57 times greater than uncleared predictions, whereas uncleared predictions of oxidised and dissolved inorganic nitrogen were conversely 1.09 and 1.05 times greater than the observed means from this catchment under cropping, respectively. Observed mean annual loads of total suspended solids, total and dissolved inorganic phosphorus, and ammonium nitrogen from the grazed catchment were 1.80, 3.11, 4.61 and 1.56 times greater, respectively, than predictions from this catchment had it remained uncleared (Table 4). In contrast, uncleared predictions of total, oxidised and dissolved inorganic nitrogen were 1.65, 39.36 and 24.79 times greater than the observed means from this catchment under grazing, respectively.

3.4. Effect of land use change on water quality

Over the 25 year period, the mean annual effect of changing land use from virgin brigalow woodland to crop or pasture resulted in 449 kg ha^{-1} yr^{-1} and 53 kg ha^{-1} yr^{-1} more total suspended solids in runoff, respectively (Table 5). Similarly, more total phosphorus, dissolved inorganic phosphorus and ammonium nitrogen were exported from crop and pasture systems than virgin brigalow woodland. Crops exported total nitrogen at an average rate of 1.04 kg ha^{-1} yr^{-1} more than if the catchment had remained uncleared, whereas pasture exported 0.74 kg ha^{-1} yr^{-1} less than if the catchment had remained uncleared. Although the cropped catchment exported more total nitrogen than its uncleared predictions, less oxidised and dissolved inorganic nitrogen were exported.

4. Discussion

4.1. Event mean concentrations

The simple hydrology and water quality model presented was effective at quantifying the effect of changing land use from virgin brigalow woodland to crop and pasture systems; however, it is likely that the results are an underestimate of the true change. Although 25 years (1984–2010) of flow data was available for these three catchments, comprehensive water quality data had only been collected for the last 10 years of this period (2000–2010). If sediment and nutrient EMCs from the agricultural catchments immediately after land use change were higher to that observed later in the study, the model would underestimate change. For example, wildfires in natural areas have been reported to increase sediment, nitrogen and phosphorus losses in runoff which typically remain high for about a year or until the soil stabilises and vegetation establishes (Ice et al., 2004; Smith et al., 2011; Stein et al., 2012). Historical cover data for the two agricultural catchments in this study indicate that plant cover was established by December 1983; C2 had 53% cover in June and 95% cover before the first crop was harvested in December, whereas C3 had 6.5% pasture cover in June and 96% cover by December. However, it is possible that the earlier runoff events may have had elevated sediment and nutrients in runoff as a residual impact of clearing and burning the catchments despite established cover.

Nonetheless, this study provides a rigorous estimate of sediment, nitrogen and phosphorus (total and dissolved) loads exported in runoff from these three catchments over 25 years. Bartley et al. (2012) reviewed sediment and nutrient concentration data from Australia suitable for catchment water quality models. Where upstream land use was dominated by more than 90% modified grazed pasture, they reported concentrations of 322 mg L^{-1} (10th and 90th percentiles 39 and 390 mg L^{-1}; n = 9 sites) for total suspended solids, 3.04 mg L^{-1} (10th and 90th 1.65 and 4.92 mg L^{-1}; n = 9 sites) for total nitrogen, and 0.73 mg L^{-1} (10th and 90th percentiles 0.17 and 2.17 mg L^{-1}; n = 17 sites) for total phosphorus. EMCs from the grazed catchment in this study for total suspended solids (229 mg L^{-1}), total nitrogen (2.17 mg L^{-1}) and total phosphorus (0.41 mg L^{-1}) are within the range of values reported by Bartley et al. (2012).

There were no dryland crop sites in the review by Bartley et al. (2012) that were dominated (> 90%) by a single upstream land use. However, plot and catchment scale data for sites with dryland crops as the main land use reported concentrations of 2501 mg L^{-1} (10th and 90th percentiles 162 and 5339 mg L^{-1}; n = 21 sites) for total suspended solids, 1.99 mg L^{-1} (10th and 90th 0.71 and 3.38 mg L^{-1}; n = 17 sites) for total nitrogen, and 0.85 mg L^{-1} (10th and 90th 0.096 and 1.65 mg L^{-1}; n = 17 sites) for total phosphorus (Bartley et al., 2012). As for the grazed catchment, EMCs from the cropped catchment in this study were within the range of values reported by Bartley et al. (2012) for total suspended solids (798 mg L^{-1}) and total phosphorus (0.93 mg L^{-1}), but total nitrogen (5.37 mg L^{-1}) values from the cropped catchment in this study were higher despite no fertiliser applications. The lower total nitrogen values reported by Bartley et al. (2012) may be partly explained by: (1) diversity of study locations, including variations in the physical and chemical structure of soil; (2) data collection from different spatial scales (plot versus small, medium and large catchments); and (3) less than 90% of the upstream catchment areas were dominated by dryland crops, which due to a potential matrix of soil type, land use and ground cover provide a less accurate comparison than if data was collected from a single land use.

Soil characteristics and land use history are of particular interest when comparing runoff water quality studies, as physically more sediment and particulate nutrients are expected from sodic soils which readily erode (Gray and Murphy, 2002) and chemically soil fertility declines over time. For example, total soil nitrogen (0–10 cm) has been shown to decline with an increase in cropping history ranging from 0 to 70 years (Dalal and Mayer, 1986a, 1986b). Following colonisation of Australia in 1788, clearing land for agriculture started in the southern states and slowly headed north to Queensland (Australian Government, 2015). For example, 85% (407,840 ha) of cropping in Australia was conducted in the southern states of Victoria, South Australia and New South Wales in 1860 with only 0.3% (1357 ha) occurring in Queensland

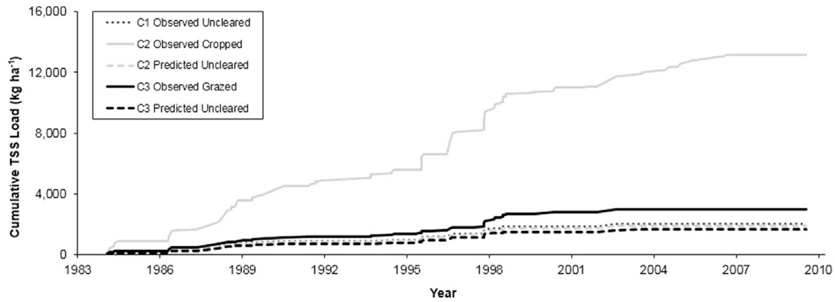

Fig. 5. Cumulative load (kg ha^{-1}) of total suspended sediments (TSS) from the virgin brigalow woodland (C1), crop (C2) and pasture (C3) catchments, and predicted loads for the cropped and grazed catchments had they remained virgin brigalow woodland. Data for the period July 1984 to January 2010; however, no events occurred between March 2007 and January 2010.

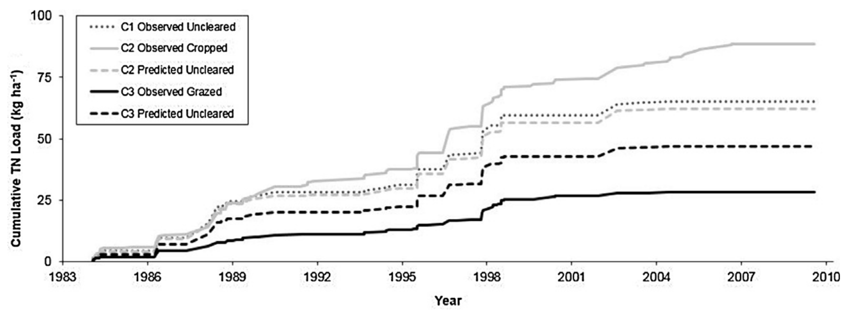

Fig. 6. Cumulative load (kg ha^{-1}) of total nitrogen (TN) from the virgin brigalow woodland (C1), crop (C2) and pasture (C3) catchments, and predicted loads for the cropped and grazed catchments had they remained virgin brigalow woodland. Data for the period July 1984 to January 2010; however, no events occurred between March 2007 and January 2010.

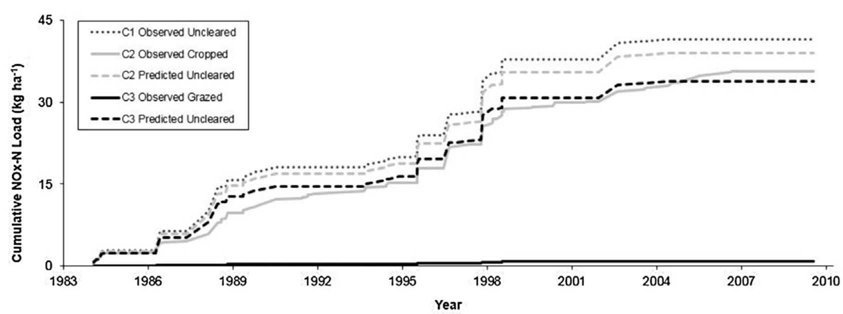

Fig. 7. Cumulative load (kg ha^{-1}) of oxidised nitrogen (NOx-N) from the virgin brigalow woodland (C1), crop (C2) and pasture (C3) catchments, and predicted loads for the cropped and grazed catchments had they remained virgin brigalow woodland. Data for the period July 1984 to January 2010; however, no events occurred between March 2007 and January 2010.

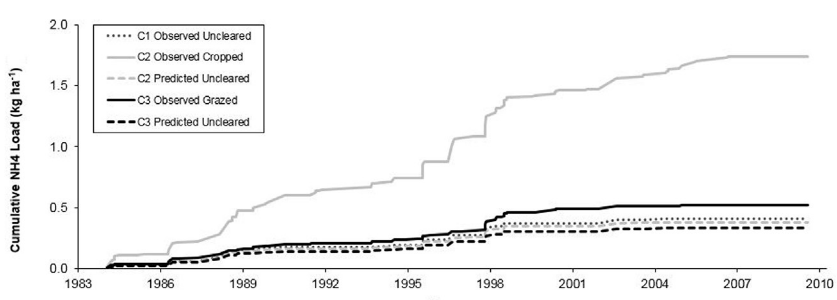

Fig. 8. Cumulative load (kg ha^{-1}) of ammonium nitrogen (NH_4-N) from the virgin brigalow woodland (C1), crop (C2) and pasture (C3) catchments, and predicted loads for the cropped and grazed catchments had they remained virgin brigalow woodland. Data for the period July 1984 to January 2010; however, no events occurred between March 2007 and January 2010.

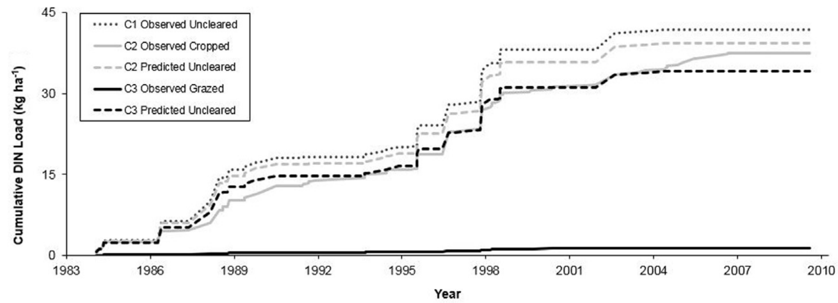

Fig. 9. Cumulative load (kg ha^{-1}) of dissolved inorganic nitrogen (DIN) from the virgin brigalow woodland (C1), crop (C2) and pasture (C3) catchments, and predicted loads for the cropped and grazed catchments had they remained virgin brigalow woodland. Data for the period July 1984 to January 2010; however, no events occurred between March 2007 and January 2010.

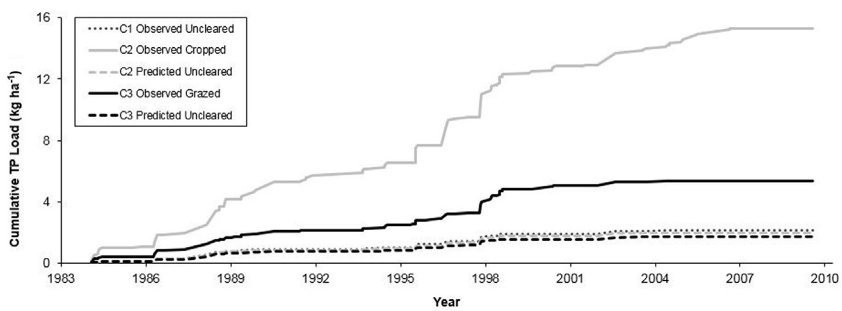

Fig. 10. Cumulative load (kg ha^{-1}) of total phosphorus (TP) from the virgin brigalow woodland (C1), crop (C2) and pasture (C3) catchments, and predicted loads for the cropped and grazed catchments had they remained virgin brigalow woodland. Data for the period July 1984 to January 2010; however, no events occurred between March 2007 and January 2010.

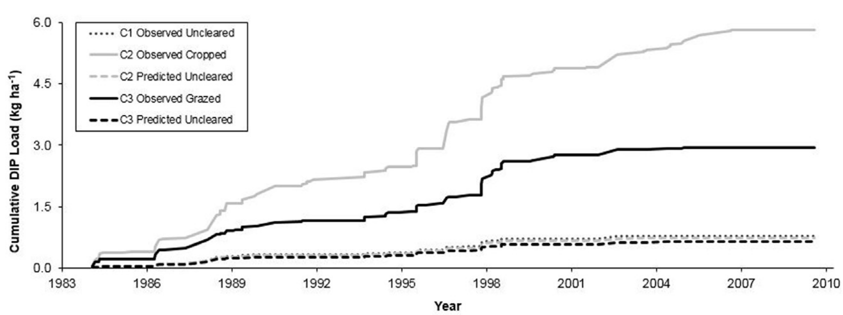

Fig. 11. Cumulative load (kg ha^{-1}) of dissolved inorganic phosphorus (DIP) from the virgin brigalow woodland (C1), crop (C2) and pasture (C3) catchments, and predicted loads for the cropped and grazed catchments had they remained virgin brigalow woodland. Data for the period July 1984 to January 2010; however, no events occurred between March 2007 and January 2010.

Table 4
Observed mean annual sediment, nitrogen and phosphorus loads (kg ha^{-1} yr^{-1}) from the virgin brigalow woodland, cropped and grazed pasture catchments over 25 years (1984–2010); and predicted mean annual loads from the cropped and grazed catchments had they remained virgin brigalow woodland.

Parameter	Load (kg ha^{-1} yr^{-1})				
	Woodland (C1)	Crop (C2)	Pasture (C3)	C2 Predicted Uncleared	C3 Predicted Uncleared
Total Suspended Solids	81	525	119	76	66
Total Nitrogen	2.61	3.53	1.13	2.49	1.87
Oxidised Nitrogen	1.66	1.43	0.03	1.56	1.35
Ammonium Nitrogen	0.02	0.07	0.02	0.02	0.01
Dissolved Inorganic Nitrogen	1.68	1.50	0.06	1.57	1.37
Total Phosphorus	0.08	0.61	0.21	0.08	0.07
Dissolved Inorganic Phosphorus	0.03	0.23	0.12	0.03	0.03

Table 5
Mean annual effect of changing land use from virgin brigalow woodland to crop and pasture systems on sediment, nitrogen and phosphorus loads (kg ha^{-1} yr^{-1}) over 25 hydrological years (1984–2010).

Parameter	Mean Annual Land Use Change Effect (kg ha^{-1} yr^{-1})	
	Crop (C2)	Pasture (C3)
Total Suspended Solids	449	53
Total Nitrogen	1.04	−0.74
Oxidised Nitrogen	−0.13	−1.32
Ammonium Nitrogen	0.05	0.01
Dissolved Inorganic Nitrogen	−0.07	−1.31
Total Phosphorus	0.53	0.15
Dissolved Inorganic Phosphorus	0.20	0.09

(Australian Bureau of Statistics, 2007). As a result, soils in the southern states where cropping has occurred for over 150 years are likely to be less fertile than in the Fitzroy Basin of Queensland where land development for cropping only commenced about 50 years ago. The shorter history of cropping at this study site in the Fitzroy Basin would also explain, at least in part, the higher total nitrogen in runoff compared to other areas of Australia which were included in the Bartley et al. (2012) review.

In contrast to total nutrients, there are limited data available on dissolved concentrations of nitrogen and phosphorus in runoff from cropped and/or grazed areas. Murphy et al. (2013) reported 5.9 mg L^{-1} oxidised nitrogen and 0.017 mg L^{-1} dissolved phosphorus from a cropped area over one wet season; whereas concentrations over 10 years used in this study were 2.17 mg L^{-1} and 0.14 mg L^{-1}, respectively. The paucity of studies that have reported on dissolved nutrients from comparative single land use systems over enough wet seasons to account for annual variability makes interpretation difficult at present. However, the EMCs used in the model presented in this study are within the range of sediment and total nitrogen and phosphorus values reported from other cropped and grazed sites. This suggests that the results are comparable to other areas dominated by similar agricultural systems.

4.2. Effect of land use change on water quality

Differences in runoff volume between the catchments can be attributed to variable water use patterns of the different vegetation types with ground cover, structural decline and surface roughness being secondary factors (Thornton et al., 2007). Clearing virgin brigalow woodland for agriculture is known to increase runoff volume (Siriwardena et al., 2006; Thornton et al., 2007), and it is well established that runoff volume and sediment loads are higher from cropped than grazed areas (Freebairn et al., 2009; Murphy et al., 2013; Sharpley and Smith, 1994; Silburn et al., 2007; Stevens et al., 2006). Both these trends were observed in this study. However, Australian literature currently provides an incomplete story on the impacts of changing land use for these two agricultural systems on nutrients in runoff. For example, Stevens et al. (2006) reported higher loads of total nitrogen and phosphorus from cropped than grazed areas but nothing on dissolved species, while Murphy et al. (2013) reported total and dissolved concentrations of nitrogen and phosphorus from cropped areas but nothing from grazed areas. This gap is also found in international studies; for example, in the southwestern United States of America, Sharpley and Smith (1994) reported higher loads of nitrogen and phosphorus (total and dissolved) following change of native grasslands to conventional tilled (fertilised) wheat but nothing from grazed areas. This highlights the uniqueness of this study's design which has collected long-term data on total and dissolved nutrients in runoff from both cropping and grazed areas concurrently with an uncleared control. In this study, more sediment and phosphorus (total and dissolved) were exported in runoff from both agricultural systems than virgin brigalow woodland. Changing land use to a pasture system also had less impact on runoff water quality than changing land use to a crop system for all sediment, nitrogen and phosphorus parameters reported.

The findings in this study also support other research which have reported a correlation between sediment and total phosphorus loss, and runoff and dissolved inorganic phosphorus loss (Gillingham and Thorrold, 2000; Hansen et al., 2002; Sharpley and Smith, 1990; Yuan et al., 2013). The considerably higher sediment loss from the cropped catchment is most likely the result of bare and/or low cover fallow management and tillage practices which are associated with erosion (Freebairn et al., 1993). Exports of sediment and total phosphorus increased at relatively proportional rates; however, the overall contribution of dissolved inorganic phosphorus to total phosphorus remained similar between the cropped catchment (38%) and its uncleared prediction (37%). This indicates that phosphorus from the cropped catchment was mainly exported in a particulate phase. Although this does not take into account the contribution of dissolved organic phosphorus which was not measured in this study, data from a nearby study has shown that dissolved organic phosphorus contributes only 3 to 5% of the total phosphorus load (Rogusz et al., 2013). This supports phosphorus from the cropped catchment being mainly exported in a particulate phase.

In contrast, the lower loss of sediment from the virgin brigalow and grazed catchments can be attributed to the higher proportion of litter and pasture cover, respectively, which protects the soil surface from raindrop impact. High ground cover also helps maintain high infiltration rates, which reduces runoff and subsequently erosion (Freebairn and Wockner, 1986; Silburn et al., 2011). Although conservative grazing of the unfertilised pasture resulted in only a 1.80 times increase in sediment compared to uncleared predictions for this catchment, total phosphorus increased 3.11 times and dissolved inorganic phosphorus 4.61 times. Furthermore, the overall contribution of dissolved inorganic phosphorus to total phosphorus increased from 37% for the uncleared prediction to 55% under grazing. The inclusion of dissolved organic phosphorus would increase the proportion of total phosphorus transported in the dissolved phase. The transport of phosphorus in mainly a dissolved phase is not surprising given the negative inverse relationship reported between dissolved phosphorus and sediment by Sharpley et al. (1981), and the management of this catchment to maintain high pasture cover and minimise erosion, which subsequently reduces particulate phosphorus loss (Sharpley et al., 1994).

The enrichment of dissolved phosphorus in runoff from the grazed catchment may also be explained by the presence of cattle, as grazing animals can return 60 to 99% of the nutrients they ingest back into the pasture system via dung and urine (Haynes and Williams, 1993). Dung is the main form that phosphorus is excreted from animals, and it often has a higher inorganic content than the pasture ingested (Haynes and Williams, 1993). For example, sheep dung has been shown to contain 80% inorganic phosphorus compared to only 64% from the pasture ingested

(Haynes and Williams, 1993). Australian data indicates that a 400 kg beef cattle steer maintaining body weight will excrete 2.8 kg of faecal dry matter per day (Department of Agriculture and Fisheries, 2011) which contains 2.1 g of phosphorus per kg of faecal dry matter (Jackson et al., 2012). Given the grazed catchment in this study is typically stocked at one 300 kg animal per 2.2 ha, approximately 0.71 kg ha^{-1} yr^{-1} of phosphorus is returned to the soil surface via dung.

Virgin brigalow woodland at this site is representative of the broader brigalow landscape in its pre-European condition, and the high nitrogen concentrations in runoff relative to the agricultural systems are likely due to the leguminous brigalow (*Acacia harpophylla*) tree which dominates the vegetation community. Although the concentration of total nitrogen in runoff from the virgin brigalow catchment was higher than the unfertilised cropped catchment, the mean annual load exported was less. This is a function of greater runoff volume and the number of days on which runoff occurred from the cropped catchment; that is, a total of 1647 mm was discharged over 99 days from the cropped catchment compared to only 663 mm discharged over 45 days from the virgin brigalow catchment over the 25 year period. This trend is similarly reported by Thornton et al. (2007) who found that in the same catchment 5.7% of rainfall become runoff in an uncleared state which increased to 11.0% under cropping.

In contrast to total nitrogen, oxidised and dissolved inorganic nitrogen both had higher concentrations and loads from virgin brigalow woodland compared to cropping. The contribution of particulate nitrogen to the total cumulative load of total nitrogen was 36% for virgin brigalow woodland and 58% for cropping; where particulate nitrogen was calculated as total nitrogen minus dissolved inorganic nitrogen. This indicates that total nitrogen load was dominated by a dissolved phase in the virgin brigalow woodland but a particulate phase in cropping. However, this does not take into account the contribution of dissolved organic nitrogen which was not measured in this study. The literature shows that dissolved organic nitrogen load in runoff can equal dissolved inorganic nitrogen loads (Heathwaite and Johnes, 1996; Martinelli et al., 2010; Rogusz et al., 2013), providing further evidence that the total nitrogen load from virgin brigalow woodland was dominated by a dissolved phase. It also suggests that total nitrogen load in cropping was likely to be equally comprised of both dissolved and particulate nitrogen if not dominated by a dissolved phase.

Although mean annual loads presented in this study are based on calculations using the 10 years of available EMC data, it is expected that total nitrogen concentrations in runoff would decline from the cropped catchment over the 25 years as nitrogen was removed from the system. Measurements of total soil nitrogen from 1981 to 2008 (the last sampling period before conversion of the cropped catchment into a ley pasture in 2010) shows that nutrient rundown occurred in the absence of fertiliser inputs and the export of nitrogen in grain and runoff. That is, concentrations of total soil nitrogen in the virgin brigalow catchment remained relatively stable (mean 0.176%) whereas concentrations in the cropped catchment declined from 0.197% in 1981 to 0.076% in 2008 (unpublished data). This result is expected given the previously reported declines in grain yield and grain nitrogen from the cropped catchment over 23 years (Radford et al., 2007).

Both agricultural systems had more ammonium nitrogen in runoff than the virgin brigalow woodland; 2% contribution to the total cumulative load of total nitrogen compared to less than 1%, respectively. However, the overall small contribution of ammonium to total nitrogen is most likely due to soil bacteria which rapidly convert ammonium into nitrate given ideal moisture and temperature conditions (Price, 2006). Cumulative losses of ammonium in runoff from this study were more similar to sediment, and hence phosphorus, than other nitrogen parameters. This trend has been reported in other studies and is attributed to the adsorption of ammonium onto sediment particles (Heathwaite and Johnes, 1996; Johnes and Burt, 1991). That is, ammonium (NH_4^+) is a positively charged cation which is attracted to the negatively charged surface of organic matter and clay particles, whereas nitrate (NO_3^-) is a negatively charged anion repelled by the soil and subsequently more readily lost via leaching and runoff.

The grazed catchment exported considerably less nitrogen than the virgin brigalow and cropped catchments. Loads of oxidised and dissolved inorganic nitrogen from pasture were almost negligible, and the higher total nitrogen loads can be attributed to particulate nitrogen. That is, dissolved inorganic nitrogen contributed only 5% to the total cumulative load of total nitrogen which indicates that particulate nitrogen strongly dominates transport from the grazed catchment. A dissolved organic nitrogen load equal to the dissolved inorganic nitrogen load would still result in particulate nitrogen strongly dominating transport from the grazed catchment. However, Radford et al. (2007) reported only 1.6 kg ha^{-1} yr^{-1} of nitrogen removal in cattle from the grazed catchment over 23 years compared to 36.1 kg ha^{-1} yr^{-1} nitrogen removal in grain from the cropped catchment. These observations imply that sown pasture in the grazed catchment is a sink for nitrogen. This is known as pasture rundown which occurs when mineral nitrogen becomes immobilised in soil organic matter and established grass plants, rather than a net loss from the system (Lawrence et al., 2014; Robertson et al., 1997). This is reflected in the soil mineral nitrogen data for the grazed catchment which remained relatively stable from 1983 to 2008 following an initial peak in 1982 due to clearing and burning of the catchment (unpublished data). Although rundown can lead to a decline in pasture productivity (Lawrence et al., 2014; Myers and Robbins, 1991), the grazed catchment in this study has always been conservatively managed to maintain high pasture cover.

Lower nitrogen from the grazed catchment compared to the cropped catchment can also be attributed to the higher percentage of nitrogen removed by pasture (3.5%) compared to cereal grains (1.8%) (The State of Victoria, 2015). As pasture tends to uptake more nitrate, a component of both oxidised and dissolved inorganic nitrogen, there is less available in the effective depth of interaction (0.1–4 cm) (Sharpley, 1985) to be dissolved and transported with water in runoff or as leachate. Loads of nitrogen in runoff have also been shown to be lower from pasture cut to 155 mm above the ground than 47 mm (Mundy et al., 2003). This supports the use of management practices that promote higher pasture biomass to reduce runoff volume and hence improve water quality, such as wet season spelling and conservative stocking rates based on feed availability.

4.3. Effect of management practices

Management practices, such as fertiliser application and tillage method, are two factors that affect the quality of surface runoff from crop systems. Sharpley and Smith (1994) found that fertiliser applications on conventionally tilled wheat resulted in a 17-fold nitrogen and 30-fold phosphorus increase in runoff. Physical and chemical degradation of soils from cropped land is a slow process (Silburn et al., 2007), and based on more than 25 years of fertility rundown at this site, soil fertility and consequently nutrient loads in runoff are expected to be lower than fertilised crops. For example, Murphy et al. (2013) reported 7–8 kg ha^{-1} oxidised nitrogen (approximately 20% of the total nitrogen applied at planting) in runoff from a fertilised crop, whereas this study in a similar area of central Queensland, Australia, reported 1.43 kg ha^{-1} oxidised nitrogen from an unfertilised crop.

Conventional tillage practices are reported to have higher runoff volume and/or erosion loss than no-till crop systems (Carroll et al., 1997; DeLaune and Sij, 2012; Ehigiator and Anyata, 2011). No-till practices have higher stubble cover which reduces overland flow velocity and the ability of water to detach and transport sediment (Rose and Freebairn, 1985). Cover levels above 30% have been suggested as critical for erosion control in crop systems (Carroll et al., 1997). Thus, management practices that retain cover and reduce runoff are also useful for reducing loads of sediment and some nutrients (Bartley et al., 2014a; Hansen et al., 2002; McIvor et al., 1995). For example, Sharpley and Smith (1994) found that changing a crop system from conventional to no-till reduced soil loss 18-fold, nitrogen loss four-fold and phosphorus loss three-fold, but an increase in bioavailable phosphorus was observed. Similarly, DeLaune and Sij (2012) reported a five-fold reduction in soil loss from no-till compared to conventional tilled systems. These authors also observed a trend of lower total phosphorus, dissolved phosphorus and ammonia nitrogen but higher nitrate nitrogen from no-till systems, although differences were not statistically different ($P < 0.05$) (DeLaune and Sij, 2012). Minimum tillage was introduced to the cropped catchment at the Brigalow Catchment Study in 1992 with intermittent use of conventional tillage practices in 1994, 1997 and 2007. Small increases in cumulative runoff and loads of sediment and nutrients can be seen around the periods when conventional tillage had been reintroduced; however, hydrology appears to be a stronger influence with the two main periods of an increased rate in cumulative loads (1991 to 1994 and 1996 to 1999) coinciding with periods of above average rainfall over multiple years. This supports the recommendation that management practices that reduce runoff also reduce sediment and nutrient loads.

Runoff water quality from pasture systems is similarly affected by cover. Silburn et al. (2011) suggested that more than 50% ground cover should be maintained in grazed areas to reduce excessive runoff and soil loss. This recommendation was based on a seven year study in a semi-arid area of Queensland which exported 30 to 50% of rainfall as runoff when cover was less than 20%, but averaged only 5.9% when cover was greater than 50%. The trend of reduced runoff, and hence reduced sediment and nutrients exported in runoff, from grazed land with higher ground cover is supported by numerous authors (Murphy et al., 2008; Nelson et al., 1996; Schwarte et al., 2011). Bare areas (scalds) have a low tolerance to soil erosion due to low total water-holding capacity which results in lower infiltration and hence increased runoff compared to areas with greater cover (Silburn et al., 2011). However, management practices such as reduced stocking rates and rotational wet season resting have been shown to increase ground cover (Bartley et al., 2010, 2014b). The pasture system at the Brigalow Catchment Study is conservatively grazed and aims to maintain at least 80% cover and less than 30% pasture utilisation, which is considered a well-managed system. Hence, the loads of sediment, nitrogen and phosphorus exported from this site may be lower than other areas which have higher stocking rates and greater pasture utilisation.

5. Conclusions

The simple hydrology and water quality model presented was based on a 17 year calibration period of the Brigalow Catchment Study in its native condition, and 25 years flow and 10 years water quality monitoring following land use change to agriculture. The model indicated that changing land use from virgin brigalow woodland to a well-managed (unfertilised) pasture system decreased nitrogen in runoff compared to runoff from virgin brigalow woodland which dominated the landscape during pre-European times; however, both crop and pasture systems increased loads of sediment and phosphorus. Overall, crops posed a greater risk to downstream water quality, and subsequently the end of catchment marine system, than pasture.

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