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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

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Abstract

The 36.7 Mha Brigalow Belt bioregion of north-eastern Australia is characterised by brigalow (*Acacia harpophylla*) vegetation on clay soils. This bioregion has been extensively cleared, predominantly for agriculture. The Brigalow Catchment Study commenced in 1965 to quantify the effects of agricultural development on water and soil resources. It is a paired, calibrated catchment study consisting of three catchments that were monitored in their virgin state for 17 years. One catchment remained virgin brigalow as a control and the other two catchments were cleared and developed for cropping or grazing. Post-development monitoring commenced in 1984 and continued for 27 years. In 2010, land management practices for cropping and grazing were modernised and another two adjacent catchments with alternative management practices were incorporated into the study. All five catchments have been monitored since 2010.

Clearing brigalow for cropping and grazing doubled total runoff, while peak runoff rates increased 96% and 47%, respectively. Various legume based pastures showed similar runoff responses. Overgrazing increased both total runoff and peak runoff rates compared to conservative grazing. Deep drainage increased from <0.34 mm/yr to 59 mm/yr under cropping and 32 mm/yr under grazing.

Soil fertility was reduced under agriculture. Total nitrogen declined 61% under cropping and 37% under grazing. Similarly, organic carbon declined 46% under cropping and 8% under grazing.

Runoff from brigalow contained 81 kg/ha/yr of total suspended solids, 2.61 kg/ha/yr of total nitrogen and 0.08 kg/ha/yr of total phosphorus. Post-development, these parameters increased 645%, 42% and 253% from cropping, respectively. Grazing increased loads of total suspended solids 146% and total phosphorus 721%; however, nitrogen was only 43% of brigalow. Legume based pastures posed a risk to water quality until the plants were well established. Overgrazing substantially increased loads of sediment and nutrients in runoff compared to conservative grazing.

The Brigalow Catchment Study has shown changes in hydrology, soil fertility and water quality resulting from developing brigalow for agriculture. This >50 year study can be considered a model in its own right and a sentinel site for management and climate impacts within the Brigalow Belt.

Introduction

The brigalow bioregions of Queensland and New South Wales occupy 36.7 million hectares, stretching from Dubbo in the south to Townsville in the north. Since European settlement, 58% of this bioregion has been cleared. In 1962, the Brigalow Land Development Fitzroy Basin Scheme commenced, resulting in the clearing of 4.5 million hectares for cropping and grazing. This clearing represents 21% of all clearing in the brigalow bioregions, and represents 32% of the Fitzroy Basin Catchment area. In order to quantify the effect of land clearing and land use change on hydrology, soil fertility and water quality, the Brigalow Catchment Study commenced in 1965 (Thornton *et al.* 2012).

Methods

Site details

The Brigalow Catchment Study (24°48’S and 149°47’E) (Figure 1) is located near Theodore in the Fitzroy Basin of central Queensland. The project is a paired, calibrated catchment study consisting of three calibrated catchments monitored since 1965 (C1 to C3), a fourth catchment monitored since 2010 (C4) and a fifth catchment (C5) monitored since 2014. The catchments vary in size from 12 to 23 ha. Soils within each catchment are predominantly Grey and Black Vertosols, with an average slope of 2.5%. In their virgin state, all catchments were vegetated with brigalow scrub communities. The region has a semi-arid, subtropical climate. Annual average hydrological year (October 1965 to September 2017) rainfall was 650 mm.

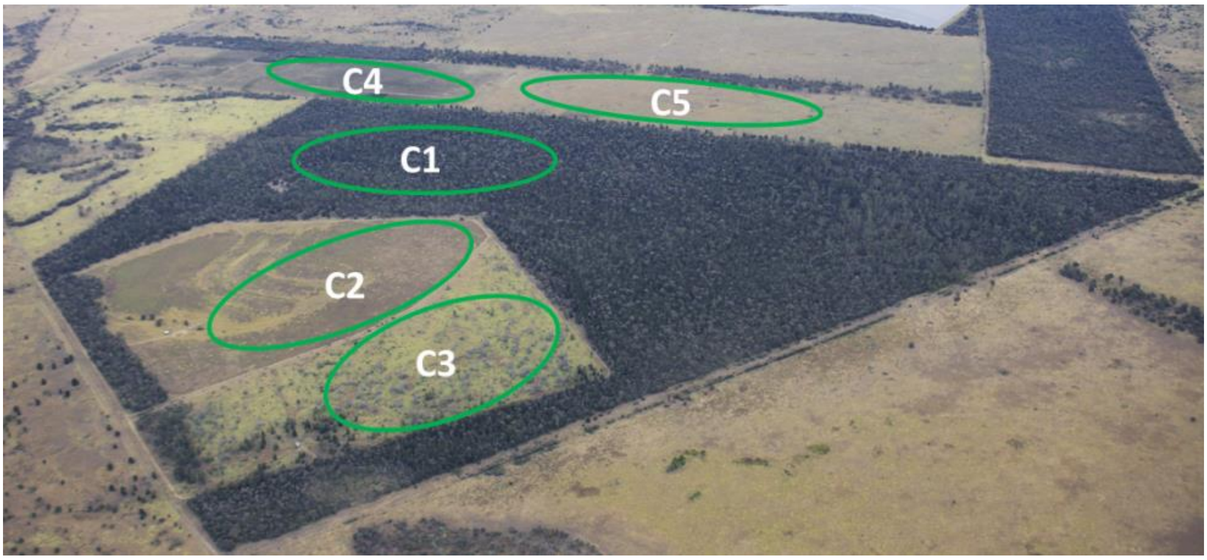

Figure 1. An aerial view of the Brigalow Catchment Study showing the five monitored catchments (C1 to C5). C1 is a virgin brigalow scrub control while C2 to C5 all currently support grazing on improved grass or improved grass and legume pastures.

The Brigalow Catchment Study can be separated into four experimental phases:

1) Calibration (1965 to 1982)

Rainfall and runoff were monitored from three contiguous catchments for 18 years. Mathematical relationships were derived to predict runoff from Catchment 2 (C2) and Catchment 3 (C3) given known runoff from Catchment 1 (C1) (Thornton *et al.* 2007).

2) Development (1982 to 1983)

Catchment 1 remained virgin brigalow scrub to provide a control treatment, while Catchments 2 and 3 were cleared and the fallen timber burnt *in-situ*. Catchment 2 was then developed for cropping with the construction of contour banks and grassed waterways, whilst Catchment 3 was developed for grazing by the planting of improved grass pasture.

3) Land use comparison (1984 to 2010)

In C2, the first crop sown was sorghum (*Sorghum bicolor*) (September 1984), followed by annual wheat (*Triticum aestivum*) for nine years. Fallows were initially managed using mechanical tillage (disc and chisel ploughs), which resulted in significant soil disturbance and low soil cover. In 1992, a minimum tillage philosophy was introduced and in 1995 opportunity cropping commenced with summer (sorghum) or winter ((wheat, barley (*Hordeum vulgare*) and chickpea (*Cicer arietinum*)) crops sown when soil water content was adequate. No fertiliser inputs were used (Radford *et al.* 2007). Catchment 3 was grazed at industry recommended stocking rates with utilisation to result in no less than 1000 kg/ha of pasture available at any time.

4) Adaptive land management (2010 to present)

Catchment 2 was planted to butterfly pea (*Clitoria ternatea* cv. Milgarra) ley pasture to restore soil fertility. Catchment 3 maintained the same treatment from the land use comparison phase however management was changed from a set stocking rate on an annual basis to variable stocking rates with the introduction of wet season spelling.
A fourth catchment, C4, was added to the study at this time. The land use of C4 was grazing on improved leucaena (*Leucaena leucocephala* cv. Cunningham) and buffel grass pasture. This catchment had a prior history of cropping and grazing before the planting of leucaena on 8 m hedgerows in 1998.

A fifth catchment, C5, was added to the study in 2014. Catchment 5 was also a grazed catchment with improved pasture (purple pigeon grass, *Seteria incrassate)* however stocking rates in this catchment were typically three times the safe long-term carrying capacity. This catchment also had a prior history of cropping and grazing before its inclusion in the study.
The two catchments added to the long-term study during the adaptive land management phase were characterised by similar soils, slope and native vegetation to the three original catchments. A calibration period in an uncleared state before their inclusion into the study was impossible due to their prior history of agricultural land use. Thus, although the two new catchments have their own unique hydrological characteristics, their relationship to the original catchments in an uncleared state is unknown.

Rainfall and runoff measurements

Each catchment was instrumented to measure runoff using a 1.2-m steel HL flume with a 3.9 by 6.1m approach box. Water height through the flumes was recorded using mechanical float recorders. Rainfall was recorded adjacent to each flume and at the head of the catchments using tipping bucket rain gauges with a 0.5 mm bucket (Thornton et al. 2007).

Drainage measurements

Deep drainage under native vegetation was determined using steady-state chloride mass balance (Silburn *et al.* 2009). Transient chloride mass balance was used to calculate deep drainage for various periods since clearing. These approaches rely on the water-soluble nature of chloride and assume complete mixing of the soil and water and one dimensional downward piston flow below the root zone. Both methods require an estimate of chloride input in infiltration and consideration of other potential sources and outputs. Chloride input was determined via soil sampling similar to soil fertility parameters (below); however, samples were taken down the profile rather than confined to the surface 0.1 m. The soil profile samples used for this deep drainage and chloride mass analysis were taken in 1981 (pre-development), 1983, 1985, 1987, 1990, 1997 and 2000.

Soil fertility measurements

Within each catchment, three permanent monitoring sites were established to monitor soil fertility. Establishment of the 20 m by 20 m sites was done using double stratification. Initial stratification was based on soil type and slope position with a monitoring site in an upper and lower-slope position on Vertosols, and the third on a Sodosol. Secondary stratification was by way of 10 sub-units, each 4 m by 10 m, within each site. Soil samples were collected from the surface 0.1 m of the soil profile at each monitoring site using manual coring tubes of 0.05 m diameter. Samples were a composite of a minimum of 8 (20 pre-clearing in 1981; and in 2008 and 2014) 0.05 m-diameter cores; 2 cores (5 pre-clearing in 1981; and in 2008 and 2014) being taken from around 4 fixed points within each sub-unit. Soil samples were collected annually from pre-clearing in 1981, to 1987 and then in 1990, 1994, 1997, 2000, 2003, 2008 and 2014, with samples retained after analysis in a long-term storage archive.

Water quality measurements

Discrete water quality samples were obtained using autosamplers (Thornton and Elledge 2016). Auto-samplers were programmed to sample every 0.1 m change in absolute stage height. 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. 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. To calculate cumulative long-term water quality loads, observed event flow from 1984 to 2010 was multiplied by the long-term EMC (2000 to 2010) for the respective catchment.

Results and Discussion

What are the impacts of land use change on hydrology, soil fertility and water quality?

In their virgin state, the catchments behaved similarly, with average annual runoff being 5% of annual rainfall. Once cleared, total runoff from the cropping catchment increased to 11% of annual rainfall and total runoff from the grazing catchment increased to 9% of annual rainfall; however, timing of the individual runoff events varied between land uses. This increase in runoff reflects water use patterns that are much more seasonal than natural vegetation. Both annual cropping and introduced pasture have significant periods of the year without transpiring plants to extract water from depth. It is suspected that this change in water use pattern is the dominant mechanism responsible for hydrologic change, with soil cover, structural decline, and surface roughness being secondary factors (Thornton *et al.* 2007).

Prior to land development, average peak runoff rates from the three brigalow scrub catchments were 3.2, 5 and 2 mm/hr for catchments 1 to 3 respectively. Peak runoff rate increased significantly from both the cropping and grazing catchments after adjusting for the underlying variation in peak runoff rate due to climatic variation between the pre- and post-development periods. The average peak runoff rate increased by 5.4 mm/hr (96%) for the cropping catchment and by 2.6 mm/hr (47%) for the grazing catchment. Increases in peak runoff rate were most prevalent in smaller events with an average recurrence interval of less than 2 years under cropping and 4 years under grazing. Soil moisture is a key driver of both runoff and peak runoff rate in this landscape (Thornton and Yu 2016).

Steady-state chloride mass balance indicated deep drainage of 0.13–0.34 mm/year across all catchments prior to land development. Large losses of soil chloride occurred under cropping and smaller losses occurred under grazing. Transient chloride mass balance gave average deep drainage of 59 and 32 mm/year for cropping and grazing catchments, respectively, during the development phase (1981–1983) when the land was bare following clearing of native vegetation and prior to establishment of crops or pastures. In the 16.7 years following establishment of agricultural land uses (1983–2000), transient chloride mass balance gave average deep drainage of 19.8 (range 3.3–50) and 0.16 (2.2 to 1.4) mm/year, respectively, in cropping and grazing catchments. The drainage rate under grazing was similar to that under brigalow scrub (Silburn *et al.* 2009)

Initial clearing and burning of brigalow scrub resulted in a temporary increase of mineral nitrogen, total and available phosphorus, total potassium and total sulfur in the surface soil (0 to 0.1 m) as a result of soil heating and the ash bed effect. Over the subsequent 32 years fertility declined significantly. Under cropping, organic carbon declined by 46%, total nitrogen by 61%, total phosphorus by 29%, bicarbonate-extractable phosphorus by 54%, acid-extractable phosphorus by 59%, total sulfur by 49% and total potassium by 9% from post-burn, pre-cropping levels. Fertility also declined under grazing but in a different pattern to that observed under cropping. Organic carbon showed clear fluctuation however no significant decline was observed. Total nitrogen declined by 37%. Total phosphorus declined by 14%, equating to only half of the decline under cropping. Bicarbonate-extractable phosphorus declined by 64% and acid-extractable phosphorus by 66%; both greater than the decline observed under cropping. Total sulfur declined by 23%; less than half of the decline under cropping. A similar decline in total potassium was observed under both land uses with a 10% decline under grazing. The primary mechanism of nutrient loss depended on the specific land use and nutrient in question but included removal in grain and beef; mineralisation and oxidation; redistribution and stratification within the soil profile and nutrient pools due to plant growth and litter recycling; uptake and storage in above ground biomass; and loss in runoff and leaching.

Long-term water quality modelling indicated that changing land use from virgin brigalow scrub to cropping or grazing increased loads of total suspended solids, total and dissolved inorganic phosphorus, and ammonium nitrogen. The well-managed (unfertilised) pasture system decreased nitrogen in runoff compared to runoff from virgin brigalow scrub (Elledge and Thornton 2017). In years when runoff occurred from the agricultural catchments but no runoff occurred from the virgin brigalow scrub, water quality loads were entirely anthropogenic and totally attributable to land use change. Certain agricultural management activities also increase water quality risk. In the cropping catchment, the largest event based total suspended solids load followed a chickpea crop with mechanical tillage for weed control in the fallow prior to and following the crop. Chickpeas leave little stubble cover to protect the soil surface from raindrop impact so preserving stubble cover with zero till fallow management both before and after the crop would likely have given a better water quality outcome. The establishment stage of pasture is, not unexpectedly, the period of greatest risk to water quality in that management system. The risk then declines over time with water quality trending towards that of long-term grazed landscapes (Thornton and Elledge 2014).

Working towards land management practice change in the wider catchment

These finding from the Brigalow Catchment Study give an indication of the effects of land use change across the broader Fitzroy Basin. This is important as the Fitzroy Basin discharges directly to the Great Barrier Reef lagoon and, according to the 2017 Scientific Consensus Statement, key Great Barrier Reef ecosystems continue to be in poor condition. This is largely due to the collective impact of terrestrial runoff associated with past and ongoing catchment development, coastal development activities, extreme weather events and climate change impacts (Waterhouse *et al.* 2017).

Under the Reef 2050 Water Quality Improvement Plan (https://www.reefplan.qld.gov.au/), using policy driven by best available science, work to decrease land-based runoff in the reef's waters is now well advanced. Significant efforts have been made to implement improved land management practices throughout reef catchments in order to decrease the flow of nitrogen, pesticides and sediments to the reef. Perhaps most relevant for a New Zealand audience is that the activities under Reef Plan appear quite similar to those listed in the current New Zealand Governments 12 Point Plan for Freshwater Quality. The lessons that Australia has learnt while running our reef plan monitoring and modelling program may well assist in delivering your policy so there is a conversation to be had.

The success of reef plan is measured by the Paddock to Reef Integrated Monitoring, Modelling and Reporting Program. The program uses monitoring and modelling tools at the paddock, catchment and marine scale to enable reporting in the short-to-medium term. The findings from studies such as the Brigalow Catchment Study are extrapolated across sub catchments using models such as HowLeaky? and APSIM. The outputs are then aggregated and routed to the basin outlet using the Source Catchments modelling platform. Using revised land management data, water quality improvements from continually improving land management practices can be estimated, allowing the Reef Plan program to evaluate, prioritise and continuously improve the efficiency and effectiveness of its on-ground actions.

Results show progress in some areas; however, faster uptake of improved land management practices is required to meet the water quality targets. The 2016 Great Barrier Reef Water Quality Report Card shows that across all reef catchments, the modelling suggests a 14% reduction in sediment loads to the Great Barrier Reef. Within the Fitzroy Basin, the modelling suggests a reduction of less than 10%.

This is a common story worldwide. The 2017 International Land Use and Water Quality conference (http://www.luwq2017.nl/) demonstrated that many countries have water quality targets but are struggling to meet them. Improved land management practices are being adopted but often won't deliver the magnitude of change that is needed to meet targets and ensure the health of waterways into the future. This is more than a green environmental issue. These are the same waterways and aquifers that provide our drinking water.

This highlights the need to develop, test and understand new land management practices to improve water quality, and will result in the next generation of new research questions for the Brigalow Catchment Study.

Conclusion

This 54 year longitudinal study clearly shows the impacts of land use change and land management on hydrology, soil fertility and water quality. The long-term data records can be considered a model in their own right and are capable of answering questions well beyond the initial scope of the study. Given the level of foresight and investment that is required to implement and maintain these experiments, it is unlikely that new studies of this nature will be commissioned. Revisiting these historical datasets and adapting the design of the ongoing experiment will allow researchers to answer new questions not thought of, or not of concern when this study commenced more than five decades ago.

Accessing the Brigalow Catchment Study

The Brigalow Catchment Study data portal provides easy access to additional information about the study and its publications. The portal also provides real time viewing of rainfall and runoff data from the study catchments. Please connect with the Brigalow Catchment Study at www.brigalowcatchmentstudy.com

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