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SOIL RESEARCH

The Brigalow Catchment Study: VI.† Evaluation of the RUSLE and MUSLE models to assess the impact of clearing brigalow (*Acacia harpophylla*) on sediment yield

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ABSTRACT

Land clearing for cropping and grazing has increased runoff and sediment yield in Central Queensland. The Brigalow Catchment Study (BCS), was established to determine the effect of land clearing on water balance, soils, and productivity, and consisted of three catchments: brigalow forest, cropping, and grazing. Factors responsible for changes in and models for predicting sediment yield have not been assessed. Objectives of this study are to identify climatic, hydrological, and ground cover factors responsible for the increased sediment yield and to assess suitable models for sediment yield prediction. Runoff and sediment yield data from 1988 to 2018 were used to assess the Revised Universal Soil Loss Equation (RUSLE) and the Modified USLE (MUSLE) to predict the sediment yield in brigalow catchments. Common events among the three catchments and events for all catchment pairs were assessed. The sediment yield was approximately 44% higher for cropping and 4% higher for grazing than that from the forested catchment. The runoff amount (Q) and peak runoff rate (Q_p) were major variables that could explain most of the increased sediment yield over time. A comparison for each catchment pair showed that sediment yield was 801 kg ha^{-1} or 37% higher for cropping and 28 kg ha^{-1} or 2% higher for grazing than for the forested catchment. Regression analysis for three different treatments (seven common events) and for different storm events (15 for forested, 40 for cropping, and 20 for grazing) showed that Q and Q_p were best correlated with sediment yield in comparison with variations in ground cover. The high coefficient of determination ($R^2 > 0.60$) provided support for using the MUSLE model, based on both Q and Q_p, instead of the RUSLE, and Q and Q_p were the most important factors for improving sediment yield predictions from BCS catchments.

Keywords: brigalow clearing, ground cover treatment, peak runoff rate, RUSLE and MUSLE, runoff, sediment yield, small dry catchments, storm events.

Introduction

Broad-scale clearing of native vegetation for agricultural systems, including grazing, has strongly affected hydrological processes and sediment yield in Australia and around the world (Siriwardena *et al.* 2006; Thornton *et al.* 2007; Ehigiator and Anyata 2011; Borrelli *et al.* 2017; Cheng and Yu 2019; Aghsaei *et al.* 2020). At the global level, soil erosion from the area of 125 million km^2 covering ~84.1% of Earth's land surface has increased by 2.5% (baseline of 35 Pg year^{-1}) due to spatial land use change occurring only in 3.3% of study area (Borrelli *et al.* 2017). In Australia, according to the Scientific Consensus Statement (Bartley *et al.* 2017), a three- and eight-fold increase in the total sediment yield has occurred across the Great Barrier Reef (GBR) catchments, depending on the region, of which approximately 80% could be attributed to changes in land

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cover. The Fitzroy Basin was identified as one of the major contributing areas for discharging large amounts of sediments into the GBR lagoon. The Brigalow Catchment Study (BCS) located near Theodore, Central Queensland, represents 36.7 Mha of brigalow bioregion of Queensland and northern New South Wales (Thornton and Yu 2016). Under the Land Development (Fitzroy Basin) Scheme, approximately 4.5 Mha of virgin brigalow forest was cleared for agriculture (including grazing), which has affected the water quality of the region (Elledge and Thornton 2017). The sediment story of the Fitzroy Basin reveals that the average current suspended sediment load exported from the Fitzroy River is between 1.5 and 2.0 Mt year^{-1} and a large quantity of load is generated due to the extensive clearing of brigalow lands since the 1950s (Lewis *et al.* 2015). The increase in sediment rates (~1.5-fold) in sediment cores from the lagoons near Rockhampton also provide evidence for increased sediment loads from the Fitzroy River since European settlement (Bostock *et al.* 2006). The brigalow clearing of the Brigalow Land Development Fitzroy Basin Scheme represents 21% of all clearing in the brigalow bioregions and 32% of the Fitzroy Basin (Queensland Department of Primary Industries 1993).

The conversion of virgin brigalow to agricultural and grazing land has altered the hydrology of small catchments in the Fitzroy Basin (Thornton *et al.* 2007; Thornton and Yu 2016). Thornton *et al.* (2007) reported increases in runoff since 1982, at the BCS, as a result of broad-scale land clearing. The runoff coefficient (the ratio of total runoff over total rainfall) has increased from 5% for the virgin brigalow catchment to 11% for cropping, and 9% for grazing (Thornton *et al.* 2007). Similarly, Thornton and Yu (2016) reported that the peak runoff rate also increased from 5 to 8.3 mm h^{-1} for cropping and 2 to 5.6 mm h^{-1} for pasture catchment, after the development of the catchments. Moreover, a comparative study over a 25-year period from 1984 to 2010 of suspended sediment data for the three catchments revealed that the total suspended solids from the cropped catchment was 6.45 times greater, and from the grazed catchment was 1.46 times greater, than the virgin brigalow (2106 kg ha^{-1}) (Elledge and Thornton 2017). Numerous studies around the world have shown the impact of land use change on sediment yield (Walling 1999; Santos *et al.* 2017; Gashaw *et al.* 2019; Aghsaei *et al.* 2020). Forest clearing since 1968 has led to a 1.8-fold increase in the annual sediment load of the Dnestr River at Sambur, Ukraine, in an 850 km^2 catchment area (Walling 1999). Sediment yield increased 10 times due to conversion of a dry tropical forest into fully developed grassland based on an experimental 2.8 ha watershed in the semi-arid Upper Jaguaribe Basin, Ceara, Brazil (Santos *et al.* 2017). Recently, conversion of forest into irrigated agriculture in one of the subcatchments in the Anzali wetland catchment, Gilan, Iran, has led to a 169% increase in the mean annual sediment yield (Aghsaei *et al.* 2020). However, no study to date has clearly demonstrated changes in sediment yield at a small scale in dry areas, and no attempt to date has been made to evaluate factors that, either individually or collectively, have caused an increase in sediment yield due to clearing of virgin brigalow forest for cropping and grazing.

As the BCS catchments are contiguous, most of the physical catchment characteristics, such as topography, soil structure and texture, are considered to be similar and effectively static. However, other factors, such as rainfall, runoff, and vegetation cover, do vary with time and may be responsible for changes in the sediment yield among the three catchments. The Universal Soil Loss Equation (USLE) (Wischmeier and Smith 1978) and its derivatives, such as the Revised USLE (RUSLE; Renard *et al.* 1997) and the Modified USLE (MUSLE; Onstad and Foster 1975; Williams 1975), provide a framework to identify and test factors that have significantly affected the sediment yield at the BCS. These erosion prediction models are the most widely used around the world for different types of land cover, because of their simplicity and flexibility. The RUSLE, which considers the erosivity index (EI_{30}) as its primary rainfall–runoff related factor, is the most commonly used model and is being applied in the Source Catchment/Dynamic SedNet modelling framework for hillslope erosion prediction for the GBR catchments (Yu 1998). The EI_{30} is the product of total amount of rainfall kinetic energy and maximum 30-min rainfall intensity (Wischmeier and Smith 1978). However, for the small dry catchments of the BCS, the EI_{30} would be essentially the same among the three different treatments. Therefore, if the RUSLE model were applied, the difference in the sediment yield would be attributed to changes in the cover and management factor (C) factor alone; C is defined as the ratio of soil loss from a field with a particular cover and management compared to a field under 'clean-tilled continuous fallow' (Wischmeier and Smith 1978). However, from previous studies (Thornton *et al.* 2007; Thornton and Yu 2016), runoff amount (Q) and peak runoff rate (Q_p) could be major factors responsible for the variation in the sediment yield among the three catchments. Several previous studies have suggested that inclusion of Q and Q_p could improve the capacity of the MUSLE model to predict the sediment yield compared with the USLE model (Kinnell 2004, 2010, 2016). Numerous studies have also suggested the appropriateness of the MUSLE model in improving sediment yield prediction under various conditions, due to inclusion of the runoff-related factors (Foster *et al.* 1982; Kinnell and Risse 1998; Erskine *et al.* 2002; Sadeghi and Mizuyama 2007; Kinnell 2010; Arekhi *et al.* 2012; Sadeghi *et al.* 2014). To test the relative contribution of Q, Q_p, and cover factors, the USLE, as modified by Williams (1975) and Onstad and Foster (1975), will be used in this study to estimate the sediment yield from different land uses because they include runoff and peak runoff rate in addition to rainfall erosivity as the rainfall–runoff related factors. As mentioned above, the RUSLE was originally developed and is widely used to estimate soil loss from hillslopes. In this study, the measured sediment yield at the catchment outlet is assumed to equal the soil loss of the catchment. Soil loss is defined as the measured total suspended solids load from a catchment. This study, therefore, assumed that there is no sediment deposition in the catchment. At the very least, the delivery ratio is constant because it was assumed constant in the Dynamic SedNet model being applied to the GBR catchments for erosion predictions (Wilkinson *et al.* 2004). However, for large catchments, the RUSLE needs a separate sediment delivery ratio to estimate the sediment yield. In contrast, the MUSLE eliminates the need for a sediment delivery ratio because runoff and peak runoff rate are closely related to sediment detachment and transport for improved sediment delivery predictions (Williams 1975).

As such, the present study had three objectives:

- to evaluate the effect of clearing brigalow for cropping or gazing on sediment yield for a subset of events over the period between 1988 and 2018,
- to test whether the change in sediment yield occurred because of the change in runoff characteristics, rather than changes in ground cover, and
- to test the applicability of using the RUSLE/MUSLE models to predict sediment yield from these small dry catchments in Central Queensland.

Materials and methods

Study area

This study was conducted in the three contiguous experimental catchments of the long-term BCS. The three catchments brigalow scrub (C1), cropping (C2), and grazing (C3) have contributing areas of 16.8, 11.7 and 12.7 ha, respectively. The BCS (24°48′S and 149°47′E) is a paired, calibrated catchment study located near Theodore in Central Queensland, Australia (Cowie *et al.* 2007). The study area is representative of 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 Brigalow Belt bioregion has undergone extensive land clearing under the Queensland Government-sponsored Fitzroy Basin Land Development scheme, which operated between 1965 and 1985 (Cowie *et al.* 2007). The area experiences a semi-arid to subtropical climate with an average maximum monthly temperature for summer of 33.1°C, while the minimum temperature in winter averages 6.5°C. The average annual rainfall is 697 mm with a range of 246–1460 mm (Cowie *et al.* 2007). The land slope within the catchments varies from 1.8% to 3.5% and averages 2.5%. Soils in the experiment catchments mainly comprise fine-textured dark cracking clays (black and grey vertosols), some with gilgais and noncracking clays (black and grey dermosols), and subdominant soil of thin surfaced dark and brown sodic texture-contrast soils (black and brown sodosols) (Cowie *et al.* 2007). The detailed description of calibration and development of these catchments is given in Cowie *et al.* (2007). The location map of the study area is shown in Fig. 1.

Site history

The study has been divided into three distinct experimental stages (Table 1) (Thornton *et al.* 2010). Stage I, the calibration

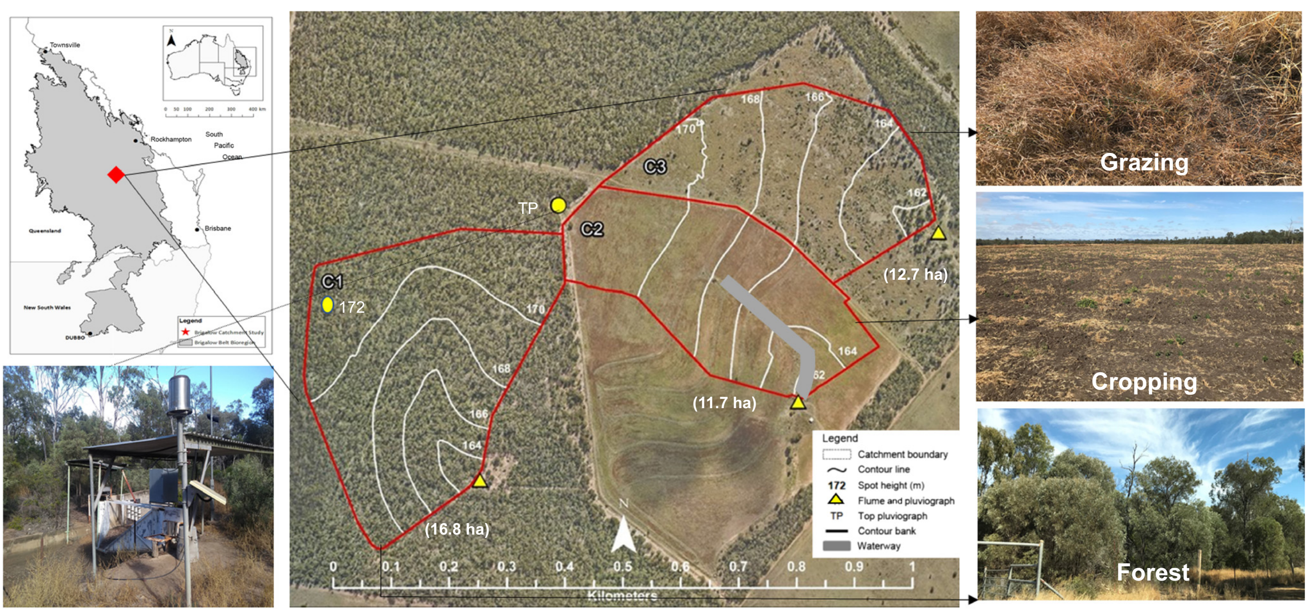

Fig. 1. Location of the Brigalow Catchment Study within the Brigalow Belt bioregion of Central Queensland, Australia, and a schematic diagram of the study site indicating the land use treatments (Thornton and Yu 2016).

Table 1. The land use history of the three catchments of the Brigalow Catchment Study.

Catchment	Area (ha)	Land use by experimental stage		
		Stage I (January 1965–March 1982)	Stage II (March 1982–September 1984)	Stage III (September 1984–December 2004)
C1	16.8	Virgin brigalow scrub	Virgin brigalow scrub	Virgin brigalow scrub
C2	11.2	Virgin brigalow scrub	Development	Cropping
C3	12.7	Virgin brigalow scrub	Development	Improved pasture

phase, commenced in 1965 with the three catchments retained in their virgin state for calibration purposes.

Stage II, the land development phase, commenced in March 1982 with C2 and C3 catchments cleared by bulldozer and chain. The fallen timber was burnt *in situ* in October 1982. In the C2 catchment, residual unburnt timber was raked to the contour line and burnt. Narrow-based contour banks at 1.5 m vertical spacing were then constructed and a grassed waterway later established. In the C3 catchment, unburnt timber was left in place, and in November 1982 the catchment was sown to improved pasture by throwing buffel grass seed (*Cenchrus ciliaris* cv. Biloela) on the soil surface. Stage II hydrology was not analysed in detail due its short duration, the marked changes in catchment condition, and a high incidence of equipment failure (Thornton *et al.* 2007).

During Stage III, the land use comparison phase, comparison of the effect of land use change commenced with cropping in C2 and grazing in C3. Sorghum was planted in C2 in September 1984 followed by nine annual wheat crops commencing in 1985. Fallow management in this period was entirely mechanical tillage. A minimum tillage and opportunity cropping philosophy was adopted in the early 1990s and has continued with either a summer (sorghum) or winter (wheat) crop sown whenever soil moisture was adequate. Grazing in C3 commenced in December 1983. Stocking rates varied between 0.29 and 0.71 head ha^{-1} (each beast typically 0.8 adult equivalents), adjusted to maintain pasture dry matter levels greater than 1000 kg ha^{-1}. No feed supplementation was provided.

Application of the RUSLE and MUSLE models for sediment yield prediction

Regression analysis was performed by using observed sediment yield and the outputs from the models: USLE (Renard *et al.* 1997), MUSLE (Williams 1975), and MUSLE (Onstad and Foster 1975) models. This analysis was performed to test the capability of the models in sediment yield prediction. The primary factors of these three models differ from each other with all the other factors remaining the same. The RUSLE model contains EI_{30}, the MUSLE (Williams 1975) model includes Q and Q_p, and the MUSLE (Onstad and Foster 1975) model contains a combination of EI_{30}, Q, and Q_p.

The equations for three selected sediment yield models can be expressed as follows.

RUSLE model (Renard *et al.* 1997)

The soil loss equation for estimating average annual soil loss is expressed as follows:

$$A = R \times K \times LS \times C \times P$$

In this study, this equation is used for estimating soil loss on event basis; therefore, it can be expressed as follows:

$$A_e = EI_{30} \times K_e \times LS \times C \times P$$

where A = average annual soil loss (t ha^{-1}), A_e = estimated event sediment yield (t ha^{-1} $event^{-1}$), R = average annual rainfall erosivity (MJ mm h^{-1} ha^{-1}), EI_{30} = rainfall erosivity factor (MJ mm h^{-1} ha^{-1} $event^{-1}$), K = soil erodibility factor (t ha^{-1} R^{-1}), K_e = soil erodibility factor (t ha^{-1} ${EI_{30}}^{-1}$), L = slope length factor, S = slope steepness factor, C = cover management factor, and P = conservation support practice factor.

MUSLE model (Williams 1975)

$$A_e = 11.8(Q \times Q_p)^{0.56} \times K_e \times LS \times C \times P$$

where A_e = event sediment yield (t ha^{-1}) by dividing runoff and peak runoff rate by catchment area and multiplying K by catchment area, Q = runoff (m^3), Q_p = peak runoff rate (m^3 s^{-1}), K_e = soil erodibility factor (t ha^{-1} ${EI_{30}}^{-1}$), and LS, C, and P are the same as for the RUSLE model.

MUSLE model (Onstad and Foster 1975)

$$A_e = (0.5EI_{30} + 15Q \times Q_p^{1/3}) \times K_e \times LS \times C \times P$$

where A_e = sediment yield (t $acre^{-1}$), EI_{30} = storm rainfall erosivity factor (foot tons per acre inches per hour), Q = storm runoff depth (in.), Q_p = storm peak runoff rate (in. h^{-1}), and K_e, LS, C, and P are the same as for the RUSLE model.

In this study, the Onstad and Foster (1975) MUSLE equation was converted to SI units using the conversions presented in (Foster *et al.* 1981). The equation in SI units can be expressed as follows:

$$A_e = (0.50EI_{30} + 3.42Q \times Q_p^{1/3}) \times K_e \times LS \times C \times P$$

where A_e = event sediment yield (t ha^{-1} event^{-1}), EI_{30} = rainfall erosivity factor (MJ mm h^{-1} ha^{-1} event^{-1}), Q = runoff (mm), Q_p = peak runoff rate (mm h^{-1}), and K_e, LS, C, and P are the same as for the RUSLE model.

Data inputs for models

In order to apply the RUSLE and MUSLE models in this study, estimations of rainfall erosivity (EI_{30}), runoff (Q), peak runoff rate (Q_p), sediment yield, ground cover data, cover management factor (C), and topographic factor (LS) are required. These parameters were determined on an event basis using BCS Stage III data from the hydrological years 1988–2018. The term sediment yield will be used throughout the paper because the present study is event based and assumed that the measured sediment yield equals the soil loss in the catchment outlet.

EI_{30}

The R represents the effect of rainfall intensity and amount of rainfall on soil erosion (Wischmeier and Smith 1978). The EI_{30} is a function of kinetic energy (E) and maximum 30-min rainfall intensity (I_{30}) (Wischmeier and Smith 1978). The BCS had two rain gauges, one sited at the discharge point of each catchment and one at the head point of all three catchments (Cowie *et al.* 2007; Thornton *et al.* 2007). The rainfall recorded at the head point of all three catchments was the most reliable and was selected as the source data to calculate EI_{30} for all three catchments. However, for some events with poor quality rainfall data, we used the rainfall data recorded from individual rain gauges installed in each catchment. In this study, storm energy (E) and 30-min rainfall intensity from 6-min rainfall data separated by an interval of 6 h were computed using the MetCal program ver. 1.7 developed by Yu (1998). MetCal uses the equation given by Renard *et al.* (1997) for calculating E for each storm event, and can be expressed as follows:

$$E = \sum_{j=1}^{n} 0.29[1 - 0.72\ \exp(-0.05I_j)]\,\Delta t$$

where I_j is the rainfall intensity for the time interval j (mm h^{-1}), Δt is the time interval (h), and n is the number of time intervals of the storm.

Q and Q_p

The Q and Q_p observations for the BCS up to 2004 are presented in Thornton *et al.* (2007) and Thornton and Yu (2016), respectively. The data collection, manipulation, and storage methodologies described in both Thornton *et al.* (2007) and Thornton and Yu (2016) were continued for the period 2004–2019, as part of the core data collection of the long-term BCS. These data sets were summarised on an event basis to determine runoff and peak runoff rate for use in this study. The study event was defined as the longest event among the three catchments: forested, cropped, and grazed.

K-factor

The K refers to the erodibility of the soil, i.e. the resistance of the soil against the aggressiveness of raindrops, runoff, or both (Djoukbala *et al.* 2019). In the present study, K was calculated using the revised nomograph equation proposed by Loch and Rosewell (1992) for Australian soil based on the original equation developed by Wischmeier and Smith (1978), using the soil texture and organic matter content. The nomograph comprises five soil and soil-profile parameters, such as percent modified silt (0.002–0.1 mm), percent modified sand (0.1–2 mm), percent organic matter (OM), class for structure (s), and permeability (p) (Renard *et al.* 1997). The equation nomograph K in t ha h ha^{-1} MJ^{-1} mm^{-1} for soils with <70% silt can be expressed as follows:

$$K = 2.77\ M^{1.14}(10^{-7})(12 - \text{OM}) + 4.28(10^{-3})(\text{SS} - 2) + 3.29(10^{-3})(\text{PP} - 3)$$

where M = (%silt + %very fine sand)(100 − %clay), OM is percentage (%) organic matter, SS is soil structure code, and PP is profile permeability class.

Additionally, K_e was also estimated using the observed sediment yield data by applying regression method using model outputs of the RUSLE, the MUSLE (Williams 1975) and the MUSLE (Onstad and Foster 1975) models. This method is most reliable for the quantification of K because it accounts for the effect of changes occurred in natural condition and, therefore, can be used to calibrate the other K calculated using different methods.

LS-factor

Sediment yield is also influenced by the length of slope (L) and slope steepness factor (S), which is referred to as the topographic factor. Since the three catchments of the BCS are adjacent and have similar size and slope (Cowie *et al.* 2007), LS was considered to be the same for each catchment and event. The L and S layer for Queensland was downloaded from the Queensland Government's

Qspatial website (https://www.data.qld.gov.au/dataset/soils-universal-soil-loss-equation-series, accessed 1 October 2019). These layers have a resolution of 30 m × 30 m and were used as input dataset in the RUSLE model in source catchment framework for erosion predictions for the GBR catchments. The *L* and *S* layers for three catchments were extracted from the layer. The *LS* was then calculated by multiplying *L* and *S*. The average *LS* for the three catchments was calculated using the Raster analysis statistics tool available in QGIS and the value of *LS* was found to be 0.28 for forested, 0.32 for cropped, and 0.39 for grazed catchments. These values were supported by data from the *LS* spatial layer used in the Queensland Government's EWater Source modelling program. (http://qldspatial.information.qld.gov.au/catalogue/custom/detail.page?fid={3F181365-702E-43FD-B54C-DD93F1A3B2CD}).

C-factor

For this study, *C* for forested (C1) and grazed (C3) catchments, and cover data for the cropping catchment (C2), were procured from Department of Environment and Science and were available on a 3-monthly basis (http://data.auscover.org.au/xwiki/bin/view/Product+pages/Landsat+Seasonal+Fractional+Cover). The *C* for forested and grazed catchments for each event was calculated as the average of the *C* of all the pixels located within each catchment. The *C* for cropped catchment was calculated by using average ground cover (%) and subfactors as advocated by Wischmeier and Smith (1978). The *C* can be expressed as follows:

$$C = \mathrm{LU} \times \mathrm{CC} \times \mathrm{SC} \times \mathrm{SR}$$

where LU is a land use subfactor, CC is a crop canopy subfactor, SC is a surface cover subfactor, and SR is a surface roughness subfactor. In this study, LU = 0.45 (Rosewell 1993) and CC = 1 due to minimal effect of canopy, and SR = 1 for smooth surface. The cover subfactor SC is calculated as follows:

$$\mathrm{SC} = \exp(-\mathrm{bcov} \times \mathrm{cover}\%)$$

where bcov = 0.035 for croplands (Renard *et al.* 1997).

Crop conservation practice factor (*P*)

The *P* represents the effect of conservation practices on water erosion processes. It varies according to the conservation techniques practiced in the watershed from 0 in the zones well protected to 1 without any conservation practices. In this study, no significant practices were performed on the catchments over time; therefore, the value of *P* was assigned as 1.

Sediment yield

Sediment yield data from 1988 to 2010 are presented in Elledge and Thornton (2017). For runoff and peak runoff rate, the data collection, manipulation, and storage methodologies described in Elledge and Thornton (2017) were continued for the period 2004–2019, as part of the core data collection of the long-term BCS. These were summarised on an event basis to determine sediment yield for use in this study.

Comparison of sediment yield from three land uses using common events

The observed sediment yield was compared among different treatments, i.e. forested (C1), cropped (C2), and grazed (C3) catchments using common events. The term *common events* refers to the runoff events filtered from the set of measured events based on the data availability and are common among the three catchments. In addition to this, we set up three paired comparisons: forest and cropped, cropped and grazed, and forest and grazed. All the runoff events from 1988 to 2018 for which the measured sediment yield was available were selected for each comparison. The total runoff and sediment yield in each treatment were compared to identify the increase or decrease in sediment yield that occurred due to land clearing.

Identification of the potential factors affecting changes in sediment yield among different land uses and different storm events

The event-based temporal variation of sediment yield and variation in factors, such as EI_{30}, Q, Q_p, and C, were graphically represented for the common events to determine the potential factors that might have changed over time and could account for the changes in sediment yield among the three treatments.

Moreover, multiple correlation analysis was performed to detect the effects of EI_{30}, Q, Q_p, and C solely on sediment yield. The analysis was undertaken for two sets of events, first to determine the factors that explain the variation in sediment yield among different storm events and the second set of events was among different land uses. The first condition considers all common events among forest, cropping, and grazing, and the second condition considers all measured events from the three treatments.

The above-mentioned facts show that the three catchments are contiguous, share similar physical characteristics, and are exposed to the same climatic sequences, except post-land development which has different hydrology (Cowie *et al.* 2007; Thornton *et al.* 2007; Thornton and Yu 2016). Hence, the difference in the estimated sediment yield among the three catchments using the RUSLE model would be driven by differences in *C*. Use of the rainfall record from the common head point of the three catchments to determine EI_{30} across all catchments is considered appropriate due to the close proximity of the gauge to the catchment outlets, which averages 550 m downslope. Although the actual rainfall erosivity may vary spatially, there are no data to indicate the magnitude of the variations. Along with rainfall, EI_{30} is also affected by the wind and topography of the catchment. Nevertheless, *LS* is also quite similar among the three catchment, therefore, it can be assumed that EI_{30} would be the same among the three catchments. Thus, runoff and peak runoff rate would be the only factors able to explain the difference in the sediment yield among the three catchments. Consequently, the MUSLE model should provide a better understanding of the effect of flow processes on sediment yield. Assuming that no change in the other factors (EI_{30}, K, LS, C, and P) occurred, the significant effect of change in hydrological factors was expected to alter the sediment yield in these catchments, suggesting that land clearing has affected the sediment yield.

Results

Sediment yield comparison among three land uses using common events

A total of seven common events for which all data were available were used to compare the runoff and sediment yield among the three treatments. Sediment yields (kg ha^{-1}) from each treatment for the seven common events are summarised in box plots, with s.d. as error bars and mean in red (Fig. 2). The mean of sediment yields were 208 kg ha^{-1} (s.d. 267 kg ha^{-1} for forested, 299 kg ha^{-1} (s.d. 406 kg ha^{-1}) for cropping, and 215 kg ha^{-1} (s.d. 336 kg ha^{-1}) for grazing. The total runoff (mm), total event sediment yield (kg ha^{-1}), and the increase in runoff and sediment yield in cropping and grazing, considering forest as the baseline, are presented in Table 2. The increase in runoff in cropping and grazing as a result of clearing was 35% and 34%, respectively. The total event sediment yield from cropping and grazing was 44% and 4% greater than for forested catchment, respectively. The difference in runoff amount between cropping and grazing catchment was almost negligible. In contrast, the cropping catchment exported 1.39 times higher loads of sediment than the grazing catchment.

Sediment yield comparison was performed using 13 common events from forested and cropping, 18 common events from cropping and grazing, and eight common events from forested and grazing. The results for total runoff (mm), observed event sediment yield (kg ha^{-1}), and the increase in runoff and sediment yield for each paired comparison are presented in Table 3. The total runoff from cropped catchment was about 55% higher than the forested catchment (456 mm) and 46% higher than the grazing catchment (444 mm). Similarly, the total runoff in grazed catchment increased by 28% compared to forested catchment (370 mm). Total event sediment yield from cropping was 2945 kg ha^{-1}, which was 1.37 times greater than that from brigalow scrub (2144 kg ha^{-1}). The total event observed sediment yield from the cropped catchment was 525 kg ha^{-1} higher than that from grazing (1767 kg ha^{-1}). Moreover, the paired study of eight common events between forested and grazing showed that the difference between the total observed sediment yield between the two treatments was approximately 28 kg ha^{-1}.

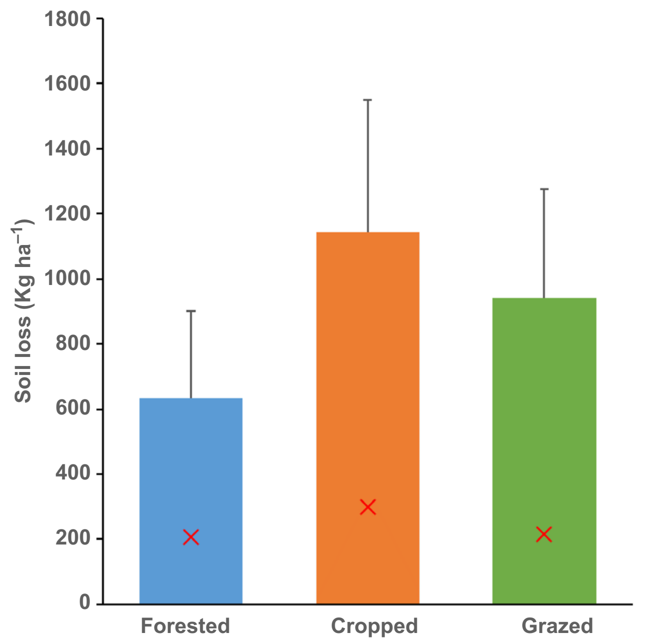

Fig. 2. Box and whisker plots showing observed soil loss (kg ha^{-1}) for seven common events for forested, cropped, and grazed catchments. Error bars represent s.d. (kg ha^{-1}), for forested (267), cropped (406), and grazed (336). × represents mean of sediment yield data ((kg ha^{-1}, i.e. 208 (forested), 299 (cropped), and 215 (grazed)).

Table 2. Total runoff and sediment yield for seven common storm events and the increase in runoff and sediment yield from C2 and C3 relative to C1.

Catchment	Total runoff (mm)	Increase in runoff from C1	Total sediment yield (kg ha^{-1})	Increase in sediment yield cf. C1
Forested	361		1453	
Cropped	486	35%	2096	44%
Grazed	484	34%	1507	4%

Determination of the factors affecting changes in sediment yield among different storm events and land uses

The event-wise variation in sediment yield and Q, Q_p, EI_{30}, and C for grazed catchment as an example is shown in Fig. 3. The figure shows that the sediment yield changed and

Table 3. Total runoff, observed event sediment yield and increase in runoff and sediment yield for paired storm events among the three surface treatments.

Catchments	Total runoff (mm)	Increase in runoff	Total event sediment yield (kg ha^{-1})	Increase in sediment yield
C1 vs C2	456		2144	
	705	55%	2945	37%
C2 vs C3	650	46%	2292	30%
	444		1767	
C1 vs C3	370		1479	
	474	28%	1507	2%

increased with an increase in Q and Q_p over time. The EI_{30} being the same among the three catchments, varied from event to event; however, the trend differed from the variation in sediment yield. The C was constant with time, which clearly was unrelated to the change in sediment yield. The temporal variation of average ground cover along with the common storm events for the three treatments from 1988 to 2018 is shown in Fig. 4.

The correlation analysis performed between the observed sediment yield and Q, Q_p, EI_{30}, and C among different land uses indicated that Q and Q_p were the best correlated factors among all factors. The correlation analysis results are presented in Fig. 5 and Table 4. The observed sediment yield was more sensitive to runoff ($R^2 > 0.78$) for all the treatments in the case of common events; however, it was the most important in forested treatment ($R^2 = 0.94$) followed by grazing ($R^2 = 0.86$). Peak runoff rate was the second-best correlated factor ($R^2 > 0.71$) among all three land uses. No significant correlation was found between C and event sediment yield ($P > 0.32$).

The results of regression analysis between the model outputs estimated from the RUSLE, MUSLE (Williams 1975), and MUSLE (Onstad and Foster 1975), and observed sediment yield, are shown in Fig. 6 and Table 4. The MUSLE model (Williams 1975), with factors Q and Q_p, was the better correlated model for forested and grazing treatments. None of the models provided any relevant correlations for the cropping catchment. For forested and grazing, the MUSLE (Williams 1975) model with Q and Q_p resulted in correlations of $R^2 = 0.59$ and 0.37, respectively, which had the best

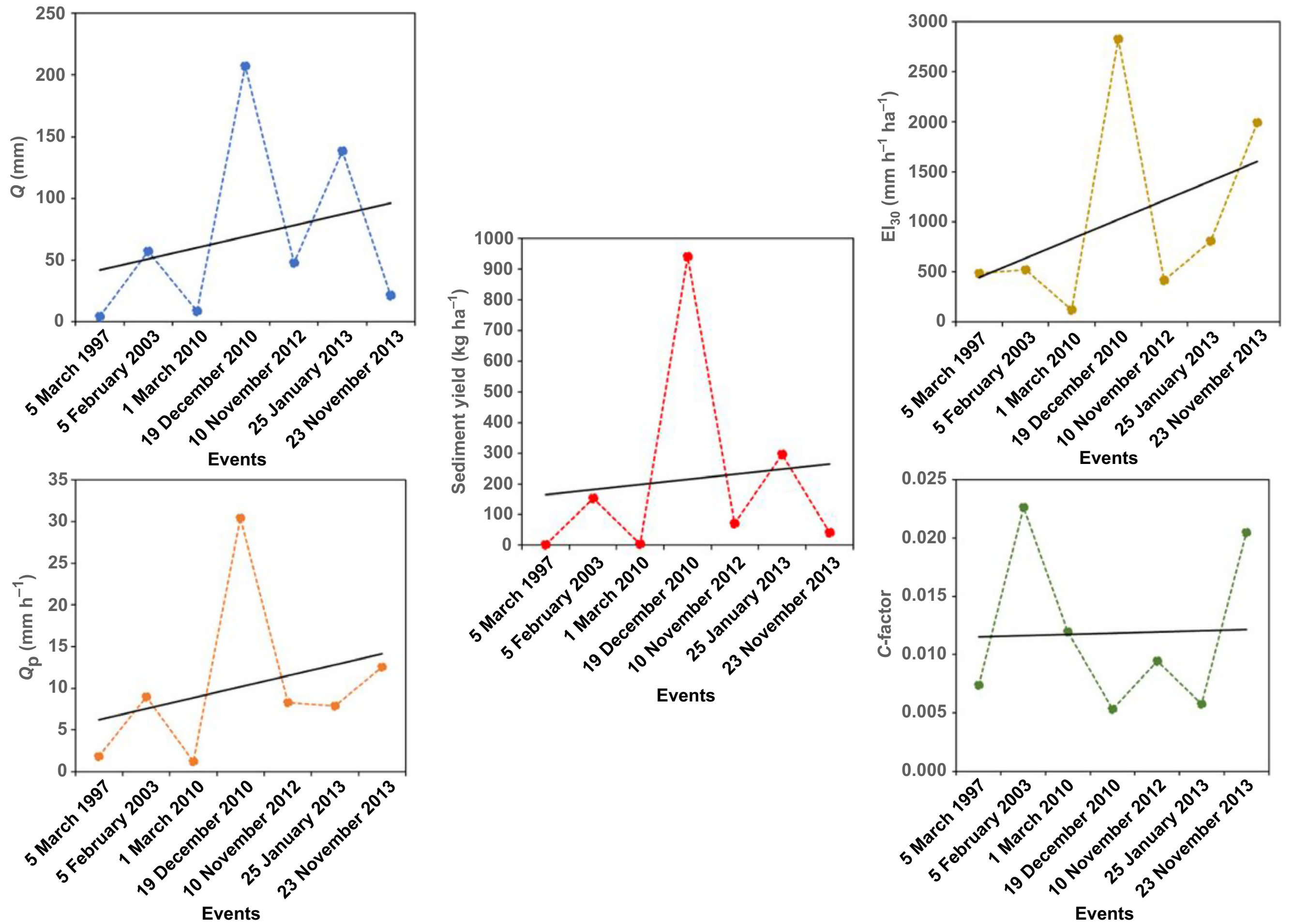

Fig. 3. Event-wise variation in event sediment yield with respect to the variation in EI_{30}, Q, Q_p, and C for seven common events for grazed catchment.

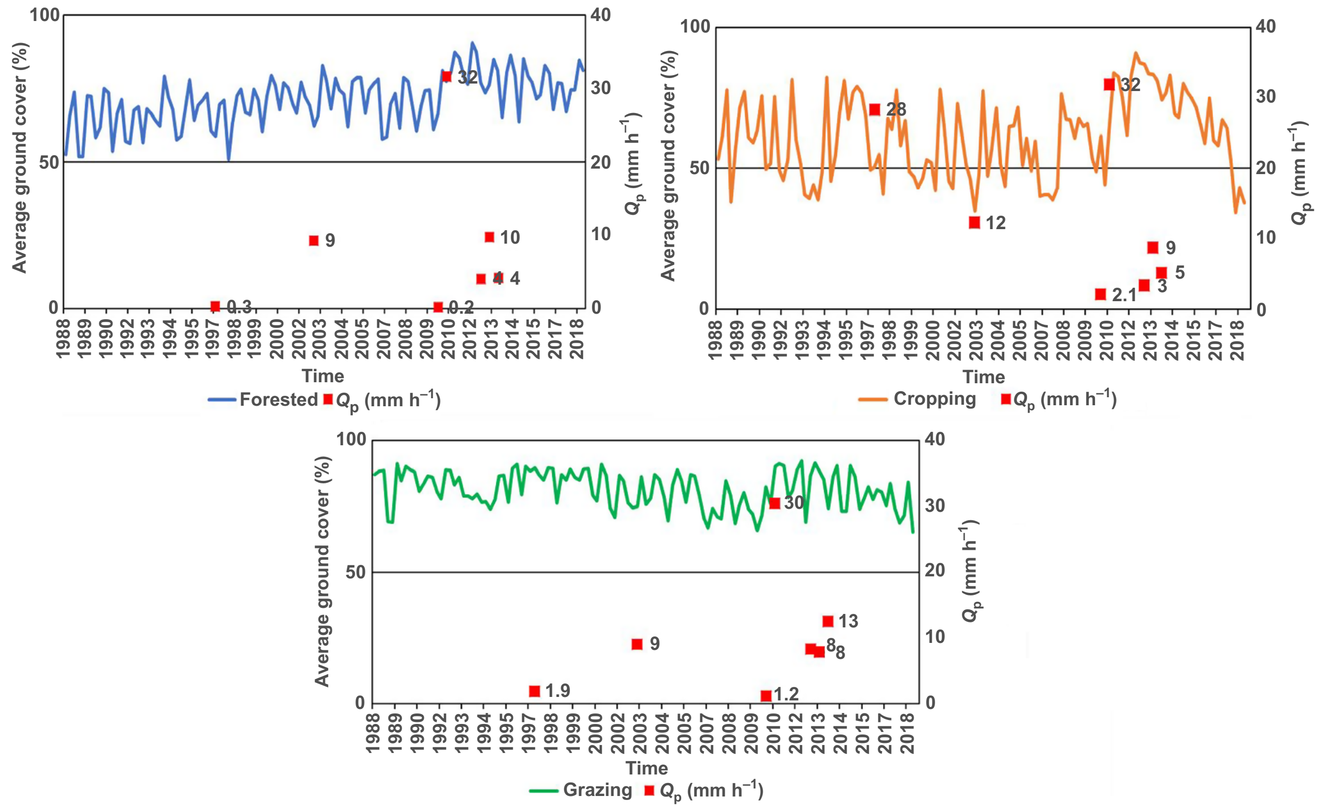

Fig. 4. Temporal variation of average ground cover for three treatments of BCS over the period from 1988 to 2018. ■ represents peak rate of runoff for the seven selected common storm events.

performance among all three models. Using the model with best correlation, i.e. the MUSLE (Williams 1975) for forested and grazing and MUSLE (Onstad and Foster 1975) for cropping treatment, the K values were estimated. The estimated K_e was 0.043 for forested, 0.016 for cropping, and 0.059 for grazing treatment. The K calculated using the nomograph method was approximately 0.03 for all three BCS catchments. The calculated and estimated K_e along with s.e. are presented in Table 5. The results of total sediment yield and increases in sediment yield using the forested catchment as baseline calculated from each treatment using the estimated K_e obtained using the best correlated model are presented in Table 6. The total estimated sediment yield from cropping was about 1.22 and 1.11 times that of forested (1446 kg ha^{-1}) and grazing (1590 kg ha^{-1}), respectively. Total estimated sediment yield from grazing was about 1.10 times that of the forested catchment (1446 kg ha^{-1}).

Among different storm events

Fifteen, 40, and 25 measured events were selected from forested, cropping, and grazing treatments for determination of the factors explaining the variation in sediment yield for different storm events. The correlation analysis between the observed sediment yield and factors Q, Q_p, EI_{30}, and C for the three treatments are shown in Fig. 7 and Table 7 (first four rows). The result shows that Q and Q_p were the best correlated factors among all factors with high R^2 value. The Q_p had the highest R^2, i.e. 0.61 for forested and 0.78 for cropping, followed by Q with R^2 of 0.28 for forested, and 0.47 for cropping; whereas, for grazing, Q was better correlated with $R^2 = 0.83$ followed by Q_p with $R^2 = 0.54$.

The regression analysis between the observed sediment yield in each treatment and the RUSLE, MUSLE (Williams 1975), and MUSLE (Onstad and Foster 1975) models revealed that the MUSLE model (Williams 1975) was the most appropriate for sediment yield estimation with higher $R^2 = 0.86$ for forested, $R^2 = 0.62$ for cropping, and $R^2 = 0.46$ for grazing (Fig. 8 and Table 7). The K_e estimated using the best correlated model, i.e. the MUSLE model (Williams 1975), for the three treatments was 0.044 for forested, 0.0132 for cropping, and 0.0543 for grazing. These K_e were similar to the K estimated for these catchments using the common events among them.

Discussion

This study investigated the effect of clearing brigalow for cropping or grazing on sediment yield from 1988 to 2018

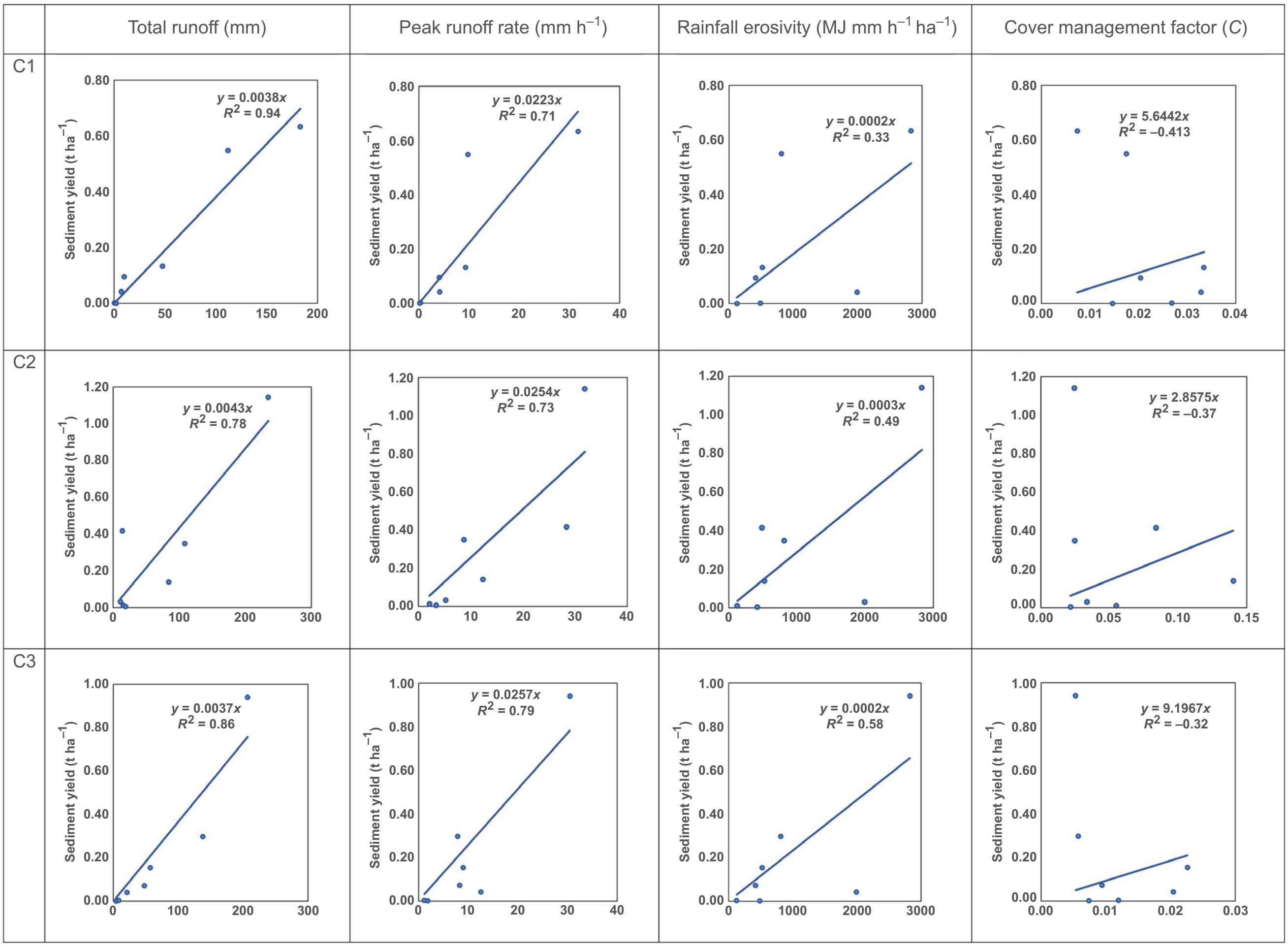

Fig. 5. Regression analyses between observed soil loss (kg ha^{-1}) and other factors (Q, Q_p, EI_{30}, and C) for seven common events among different treatments, i.e. forested (C1), cropping (C2), and grazing (C3).

Table 4. Correlations between event sediment yield and its predictors for seven common storm events among different land uses.

Factors	Coefficient of determination (R^2)		
	Common events		
	Forested	Cropped	Grazed
Runoff	0.94	0.78	0.86
Peak rate of runoff	0.71	0.73	0.79
Rainfall erosivity factor	0.33	0.49	0.58
RUSLE	0.39	0.16	0.21
MUSLE (Williams 1975)	0.59	−0.002	0.37
MUSLE (Onstad and Foster 1975)	0.18	0.17	0.20

and tested whether the changes in sediment yield occurred because of the change in runoff characteristics, more so than changes in ground cover. In addition, applicability of the RUSLE/MUSLE models was tested to predict the sediment yield from these dry catchments in Central Queensland. The study assumed that the measured sediment yield was equal, or at least proportional, to the soil loss from the catchment.

Total event sediment yield from the cropped and grazed catchments had significantly increased due to conversion of brigalow forest to cropping and grazing. As illustrated in Table 2, the sediment yield from cropping and grazing was 44% and 4% higher than for forested catchment, respectively. Similarly, the comparative study between paired catchments (forested vs cropped, cropped vs grazed, and forested vs grazed) revealed that sediment yield from cropping increased by 37% and 30% compared with forested and grazed catchments, respectively. These findings were consistent with previous studies in that changes in land use and land cover could lead to an increase in sediment yield. For example, a study of the Dnestr River at Sambur, Ukraine, with a catchment area of 850 km^2, showed that forest clearing in the catchment after 1968 led to a 1.8-fold increase in annual sediment load of the river (Walling 1999). The sediment yield from a 2.8 ha catchment in the semi-arid region Ceara, in the Upper Jaguaribe Basin, Brazil, increased 10 times due to

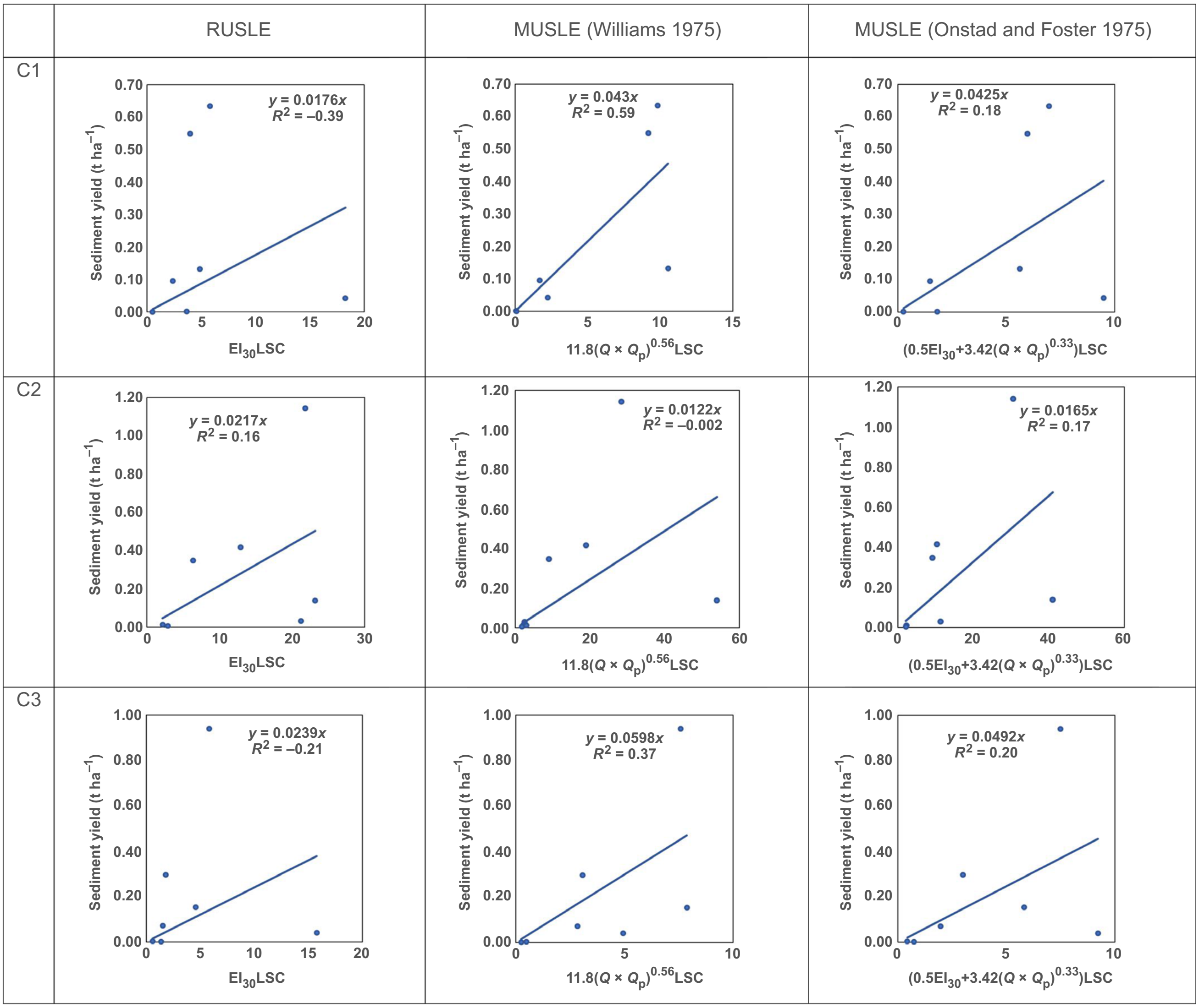

Fig. 6. Regression analyses between observed soil loss (kg ha^{-1}) and model estimates of the RUSLE, MUSLE (Williams 1975), and MUSLE (Onstad and Foster 1975) models using seven common events among forested (C1), cropping (C2), and grazing (C3) treatments.

Table 5. $K \pm$ s.e. estimated using different methods for three catchments.

Catchments	Nomograph K	RUSLE K_e	MUSLE (Williams 1975) K_e	MUSLE (Onstad and Foster 1975) K_e
Forested	0.03	0.017 ± 0.015	0.043 ± 0.010	0.042 ± 0.017
Cropped	0.03	0.021 ± 0.009	0.012 ± 0.006	0.016 ± 0.007
Grazed	0.025	0.023 ± 0.021	0.059 ± 0.022	0.049 ± 0.022

conversion of a dry tropical forest in 2009 into full developed grassland by 2011 (Santos *et al*. 2017). A previous study at the BCS, Central Queensland, identified the effect of land use change on sediment loads exported from the catchment over 25 years, and showed that the total suspended solids from the cropped and grazed catchment was about 6.45 and 1.46 times greater than for virgin brigalow (2106 kg ha^{-1}) (Elledge and Thornton 2017). The conversion of forest into irrigated agriculture in one of the subcatchments in the Anzali Wetland catchment, in Gilan, Iran, led to an increase of 169% in the mean annual sediment yield (Aghsaei *et al*. 2020). Although these studies conducted across the world have shown the increase in sediment yield due to land use change, the magnitudes of the increase in sediment yield due

Table 6. Total estimated sediment yield (kg ha^{-1}) among C1, C2, and C3 calculated using Q and Q_p with K_e = 0.044 (forested), 0.0165 (cropping), and 0.059 (grazing).

Catchments	Total estimated event sediment yield (kg ha^{-1})	Increase in sediment yield from C1
Forested	1446	
Cropped	1760	22%
Grazed	1590	10%

Table 7. Correlation between event sediment yield and its predictors among different storm events of the three catchments.

Factors	Coefficient of determination (R^2)		
	All events		
	Forested	Cropped	Grazed
Runoff	0.28	0.47	0.83
Peak rate of runoff	0.61	0.78	0.54
Rainfall erosivity factor	0.21	0.042	0.38
Cover management factor (C)	0.11	0.026	−0.15
RUSLE	0.27	−0.051	−0.023
MUSLE (Williams 1975)	0.86	0.62	0.46
MUSLE (Onstad and Foster 1975)	0.65	0.16	0.30

to land use conversion were somewhat different from the aforementioned previous studies. This is mainly because the present study was carried out on a very small paddock-scale area located in a semi-arid region. This study has clearly shown the increase in the sediment yield due to clearing of virgin brigalow forest for cropping and grazing, in small dry catchments over a relatively long period of time. The variability in the sediment yield was not only assessed among the three land uses but also among the different storm events. This variability of sediment yield was accompanied by temporal variations in other factors such as EI_{30}, Q, Q_p, and C; therefore, the present study has a limited number of common events for comparison purpose.

In this study, using the sediment yield models RUSLE and MUSLE, Q and Q_p were shown to be the major potential factors or variables that caused the increase in the sediment

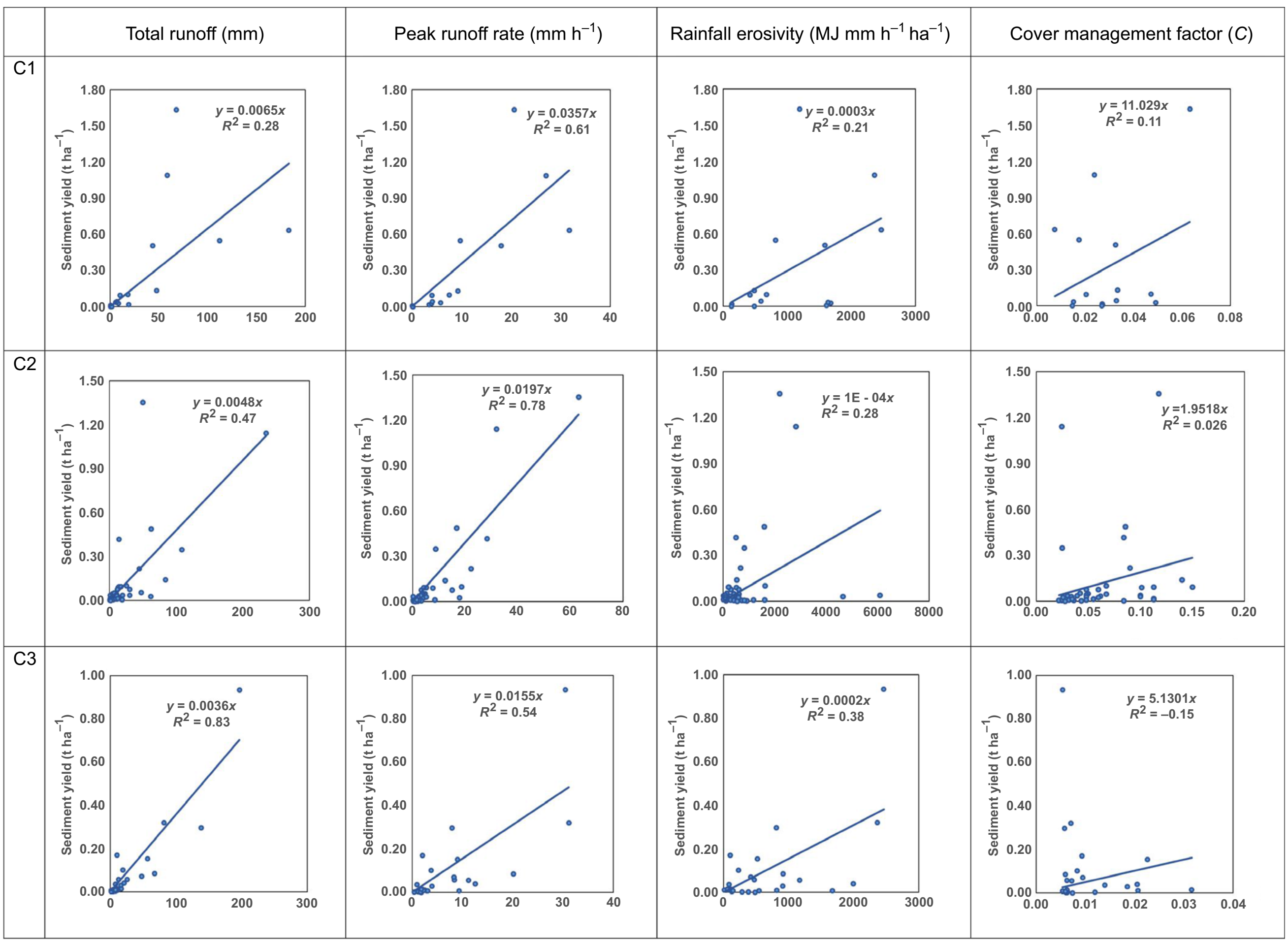

Fig. 7. Regression analyses between observed soil loss (kg ha^{-1}) and other factors (Q, Q_p, EI_{30}, and C) for 15, 40, and 20 storm events of forested (C1), cropping (C2), and grazing (C3) treatments.

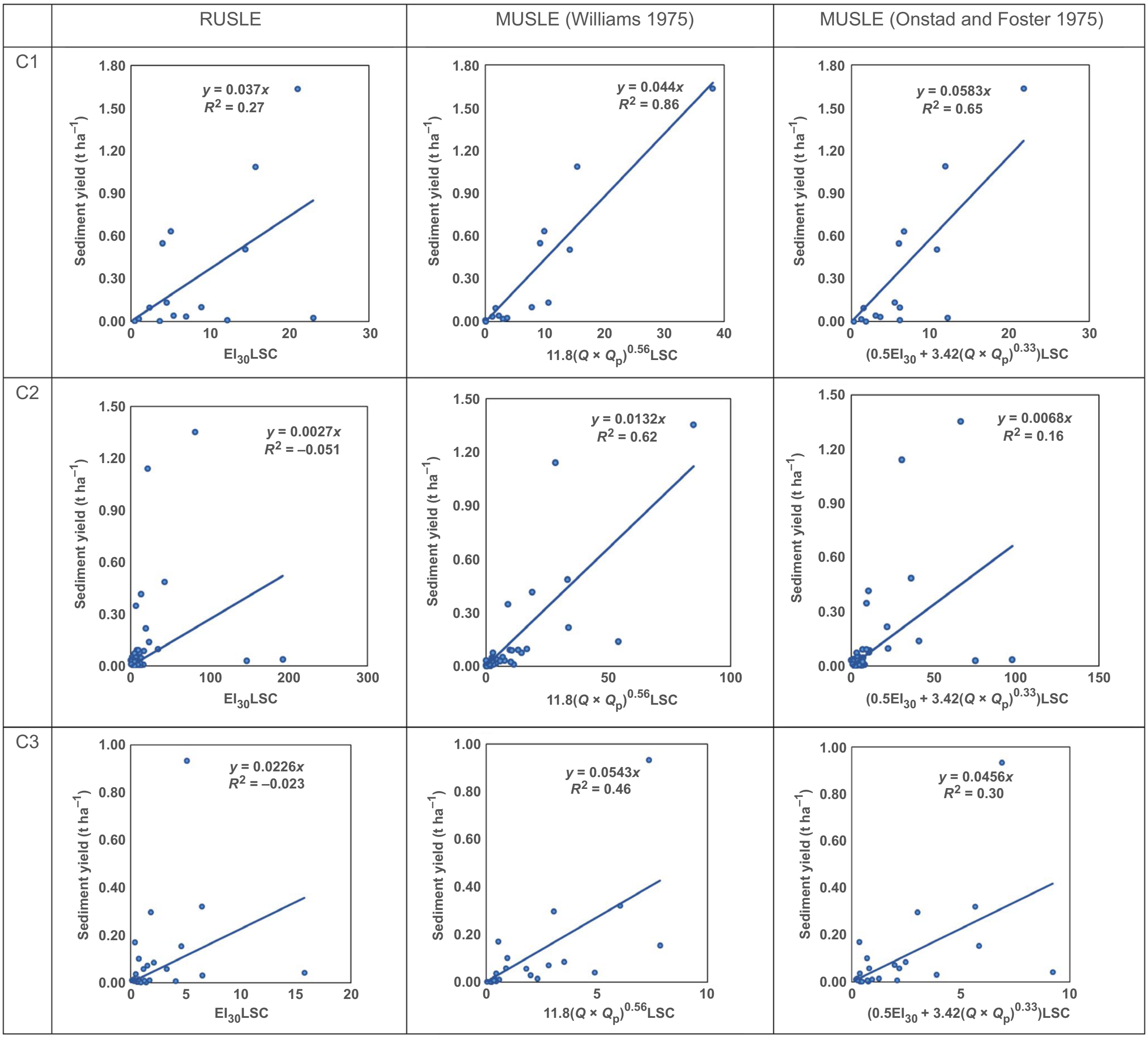

Fig. 8. Regression analyses between observed soil loss (kg ha^{-1}) and model estimates of the RUSLE, MUSLE (Williams 1975), and MUSLE (Onstad and Foster 1975) models using 15, 40, and 20 storm events of forested (C1), cropping (C2) and grazing (C3), respectively.

yield in the cropped and grazed catchments after land clearing. The temporal variation in C was quite low and did not show a significant relationship with the increase in sediment yield. Rainfall erosivity cannot explain the variation in event sediment yield among the three catchments because the value of EI_{30} is the same for individual events among the three treatments, and therefore when using the MUSLE model, rainfall erosivity could not be related to the increase in sediment yield from cropping and grazing catchments. Therefore, it was only Q and Q_p that varied and increased since clearing and have been the principal cause of the increase in sediment yield for these brigalow catchments. The results of the correlation analysis performed between the observed sediment yield and the factors Q, Q_p, EI_{30}, and C for the three catchments among the different land uses showed that Q and Q_p were the best correlated factors to explain variations in the observed sediment yield with $R^2 > 0.78$ and $R^2 > 0.71$, respectively, for all treatments. Additionally, correlation analysis between the observed sediment yield and Q, Q_p, EI_{30}, and C for the three treatments among different storm events revealed that the effect of Q and Q_p outweighed the effect of EI_{30} and C on sediment yield. The peak runoff rate, Q_p, had a higher R^2 value (>0.61) for forest and cropping and equal to 0.54 for grazing, whereas the runoff amount had the highest R^2 (0.83) for grazing followed by cropping ($R^2 = 0.47$) and forest ($R^2 = 0.28$). The results were similar to the findings that sediment yield from catchments at three spatial scales (1 m^2, 20 m^2, and 2.80 ha) mainly depends on runoff, with $R^2 > 0.70$ (Santos *et al.* 2017). Likewise, runoff explains 58% of the variance in sediment yield from the Magdalena catchment (257 438 km^2), Colombia (Restrepo and Syvitski 2006).

The present study also illustrated that among the three sediment yield models, i.e. RUSLE, MUSLE (Williams 1975), and MUSLE (Onstad and Foster 1975), that the MUSLE (Williams 1975) model had the higher capacity to predict sediment yield from the BCS catchments, especially the grazed catchment. The results from the regression analysis between the model estimates from the RUSLE, MUSLE (Williams 1975), and MUSLE (Onstad and Foster 1975) models and observed sediment yield among the three treatments and different storm events suggested that, except for the cropped catchment, sediment yield was very sensitive to primary factors of the MUSLE (Williams 1975) model, i.e. Q and Q_p. In addition, with regards to K, direct measurement of K is often quite expensive and time consuming (Loch *et al.* 1998). The USLE-based nomograph K, which is currently used in the eWater Source Catchments modelling framework of the GBR Paddock to Reef Integrated Monitoring, Modelling and Reporting Program for sediment yield modelling, is the best K to use for ungauged catchments without measured soil loss or sediment yield (Loch *et al.* 1998). Additionally, the estimated K_e obtained using the MUSLE model, either as it is or with some modifications with respect to the change in the real sediment yield data, can also be used to estimate sediment yield from the BCS catchments. For the cropped catchment, the estimated K_e was very close to the nomograph-based K; however, for the grazing catchment, the nomograph K needs some modifications with respect to real sediment yield data for use in the MUSLE model. Bosomworth *et al.* (2018) also indicated that the RUSLE-based nomograph K overestimated soil loss by approximately 50% in most cases of grazed soils. Although, adjustment is required, the difference between the nomograph and estimated K_e was not high enough to affect sediment yield estimation in any of these catchments. These observations provided support for the application of MUSLE (Williams 1975), with the inclusion of Q and Q_p instead of EI_{30}, for sediment yield prediction in BCS catchments.

As the RUSLE model does not consider Q and Q_p for sediment yield estimation, any change in sediment yield among the three catchments will be related to either K_e or C, because EI_{30} was the same among the three treatments. However, K_e was estimated using the observed sediment yield; therefore, any change in other factors can only affect K. Hence, considering just change in C, we found that the ground cover in all three catchments was constantly higher with time and could not explain the increase in sediment yield. Therefore, we cannot use the USLE/RUSLE model to predict sediment yield for the three treatments. In contrast, it was observed that Q and Q_p were the only factors that could be responsible for the change in sediment yield. The changes in Q and Q_p due to the clearing of brigalow forest for cropping and grazing have been recorded in previous studies conducted by Thornton *et al.* (2007) and Thornton and Yu (2016). In the present study, Q and Q_p dramatically increased due to land conversion. The effect of shear stress due to runoff factors has led to the detachment and transport of soil particles within the catchments. Therefore, the findings in the present study provide strong evidence that the increase in Q and Q_p caused the increase in sediment yield among the three catchments over time. Moreover, the study clearly indicated that the MUSLE (Williams 1975) model was the most appropriate for sediment yield predictions in the BCS catchments. The reason behind the lack of capability of other two models, i.e. the RUSLE and MUSLE (Onstad and Foster 1975) models, was the small catchment area and also the lower amount of rainfall and rainfall intensity that produced low rainfall erosivity, which was insufficient to generate a modelled sediment yield.

The present study was based on the premise that there is no sediment deposition, i.e. the measured sediment yield at the catchment outlet was assumed to equal the soil loss from the catchment, where soil loss is defined as the measured total suspended solids load from a catchment. However, this assumption is inappropriate for large catchments, where the sediment delivery ratio needs to be considered explicitly for hillslope erosion prediction. For most of the Fitzroy Basin, the hillslope sediment delivery ratio (HSDR) was assigned a value of 0.1 in the dynamic SedNet model (Dougall *et al.* 2014). In contrast to the RUSLE model, the MUSLE model can be used directly for predicting sediment yield due to its consideration of runoff amount and the peak runoff rate, which eliminates the need for HSDR. However, for an ungauged catchment, the modified version of the USLE model can be used to estimate soil loss and sediment yield, and the combined sediment yield can be validated against the measured sediment data at the mainstream of the basin. Moreover, the ability of the USLE model can be improved by including the sediment transport capacity by stream flow process which leads to the estimation of soil loss or sediment yield at the catchment outlet. A modified version of USLE, i.e. USLE-M proposed by Kinnell and Rise (1998), which considers rainfall and runoff erosivity, has the capability to predict event soil loss better than USLE and, being a transport limited model, it can also predict the deposition occurring within a catchment (Kinnell 2015, 2016). The current study not only evaluated the effect of land clearing on sediment yield, but also assessed the alternative models, involving runoff characteristics for improved sediment yield predictions.

Conclusion

The aims of the present study were to evaluate the effect of land clearing for cropping and grazing in brigalow catchments on sediment yield, and to identify the factors or processes responsible for the increase in the sediment yield that occurred due to land use change. Moreover, the study examined the capability of sediment yield models, i.e. RUSLE, MUSLE (Williams 1975), and MUSLE (Onstad and Foster 1975), for estimating sediment yield from BCS catchments. The study involved the simple and direct comparison of observed total event sediment yield from different treatments and different storm events. The comparative study showed that the sediment yields significantly increased in cropped and grazed catchments following land clearing, and that the runoff amount and peak runoff rate were the main factors that changed over time and explained most of the variation and increase in sediment yield compared to the effect of ground cover. The regression analysis performed between the observed sediment yield and the factors Q, Q_p, EI_{30}, and C, revealed that the Q and Q_p were the factors with best correlations and, thus, can be responsible for the changes in sediment yield from different land uses and different storm events. Moreover, the correlation between the observed sediment yield and the outputs of the three sediment yield models, each having a different model structure, revealed that the MUSLE (Williams 1975) model, which considers Q and Q_p as its primary factors, was better able to appropriately predict sediment yield from the BCS catchments. This study clearly showed that the increased sediment yield was mostly caused by the increase in the runoff and peak runoff rate parameters Q and Q_p. Previous studies conducted on the BCS catchments observed that changes in Q and Q_p occurred due to conversion of brigalow forest to cropping and grazing, and the present study provides strong evidence that the inclusion of Q and Q_p as the primary factors can improve sediment yield predictions from brigalow catchments.

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Data availabilty. Data collected through the Brigalow Catchment Study can be accessed via the data portal (http://www.brigalowcatchmentstudy.com/BCSportal.html). Topography and ground cover data are available at (https://www.data.qld.gov.au/dataset/soils-universal-soil-loss-equation-series) and (http://data.auscover.org.au/xwiki/bin/view/Product+pages/Landsat+Seasonal+Fractional+Cover). Further details are available upon request to authors.

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