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Sustainability of beef production from brigalow lands after cultivation and mining. 2. Acland Grazing Trial pasture and cattle performance

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Abstract

Context. Agricultural land used for open-cut coal mining in Queensland is required by law to be returned to a safe, stable and self-sustaining state for agriculture.

Aims. The aim of this research was to identify whether rehabilitated pastures on post-mine soil at a site near Acland could viably support cattle production.

Methods. Five years of field data from Botanal pasture assessments, pasture quality, cattle liveweights and faecal observations, plus supplementary cattle liver data, were used to compare pasture and cattle performance from mined and unmined previously cultivated brigalow land. Subtropical pasture species were sown in 2007 (Rehab1, 22 ha), 2010 (Rehab 2, 32 ha) and 2012 (Rehab3, 22 ha) in three rehabilitated paddocks and in 2012 in an unmined (Control, 21 ha) paddock. The paddocks were grazed for 117–190 days of each year by Angus cattle.

Key results. Mean total standing dry matter in grazed pasture over the five trial years was consistently higher in Rehab 2 (5656 kg/ha) than in the other paddocks. Rehab 1 (3965 kg/ha) and Rehab 3 (3609 kg/ha) performed at an intermediate level and the Control paddock produced less pasture (2871 kg/ha). Grass leaf crude protein was higher in Rehab 2 than in the other paddocks and declined significantly ($P < 0.001$) across all paddocks as pasture aged. Pasture species remained perennial, palatable and productive in all paddocks; however, pasture yield, quality and composition trends over time suggested that pasture rundown occurred across all paddocks. The mean liveweight gain (LWG) per head when grazing the trial paddocks (trial LWG) was higher ($P < 0.05$) in the Rehab 2 cohort than the other paddock cohorts in Years 3 and 5, and trial LWG in the Control cohort was not significantly ($P > 0.05$) different from one or more of the rehabilitated paddock cohorts each year. Cattle production per hectare during the trial grazing periods was also consistently highest in Rehab 2 (5-year mean trial LWG 131 kg/ha) compared with the other paddocks (67–80 kg/ha).

Conclusion. The rehabilitated pastures in use by the mine were considered at least as productive as the surrounding unmined brigalow landscape.

Implications. The Acland rehabilitation process was considered successful in establishing pastures that were able to viably support cattle production.

Keywords: rehab, rehabilitation, Botanal, nitrogen, subtropical, GRASP, cattle.

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Introduction

Agricultural land used for open-cut coal mining in Queensland, Australia, is required by law to be returned to a safe, stable and self-sustaining state for agriculture (Queensland Government 2014; Butler and Anderson 2018). The performance of pasture rehabilitation programs has been measured at numerous mines, with a justifiable focus on environmental outcomes (e.g. stability and erosion control) more so than on agricultural benchmarks (Grigg *et al*. 2000). Authentic examples of post-mine land uses can help stakeholder discussions aimed at increasing the rate of transition of post-mined land into productive uses

(Maczkowiack *et al*. 2012; Everingham *et al*. 2018). Livestock grazing of pastures on rehabilitated land is a potential post-mine land use (Mentis 1999; Ditsch *et al*. 2006); however, there are few published examples of the viability of such rehabilitation in Australia. Bisrat *et al*. (2004) and Grigg *et al*. (2002) found that the calculated safe stocking rate for sown buffel grass pastures and cattle liveweight gain observed over 18 months on rehabilitated mining land at two sites in central Queensland was comparable to that on unmined land in the region. At a third mine, the safe stocking rates were lower due to steep slopes and sodic soils. Vickers *et al*. (2012) also concluded that steep and dissected terrain and low biomass production made rehabilitated native grassland in north-western Queensland unsuitable for grazing. Two trials in the Hunter Valley region of New South Wales found that cattle grazing sown pastures on rehabilitated mining land performed well compared with cattle grazing nearby native pastures (Anonymous 2015; Griffiths and Rose 2017). A comparison of the viability of sown pastures dominated by Rhodes (*Chloris gayana*) and/or panic (*Megathyrsus maximus*) grass for cattle production on rehabilitated and unmined land has not been published.

The Acland open-cut coal mine is in subtropical south-eastern Queensland and has been in operation since 2002, mining the underlying Jurassic Walloon coal measures. The mine uses a continuous mining and rehabilitation process that slowly advances across the landscape at 10–15 ha per year. Prior to mining, the mining lease was used for dairying, beef and crops. Since mining began, unmined land on the mining lease has been used mainly for beef cattle grazing and, partially, for dryland winter wheat and barley cropping. The land is within the Acland Land System (Vandersee and Mullins 1977), and the lease sits on the Poplar Box Walloon landform, which supports several land resource areas, including the Brigalow Uplands on which the majority of mining has occurred (Bennett *et al*. 2021). Brigalow Uplands typically support brigalow (*Acacia harpophylla*), belah (*Casuarina cristata*) and wilga (*Geijera parviflora*) open forest vegetation on soils derived from the Walloon sandstones but also Mountain Coolibah (*Eucalyptus orgadophila*) and softwood scrub species such as bottle tree (*Brachychiton*) and crows ash (*Flindersia australis*) with brigalow on basalt rises. Dermosol (gradational clay) and Vertosol (cracking clay) soils derived from the fine-grained Walloon sandstones and/or overlying basalt flows dominate the lease.

The post-mining objective of the mine was to return mined land to pastures that can support commercial livestock grazing. In 2018, ~350 ha of the mining lease was certified as rehabilitated by the state government, representing the largest single area of certified rehabilitation for an open-cut coal mine in the state of Queensland (New Hope Group 2018). The next step is for environmental authority for public release of the land.

The aim of the present research was to investigate whether the Acland rehabilitated pastures can viably support cattle production. To evaluate this aim, pasture and livestock performance on Acland rehabilitated mining land that was sown 2–7 years prior, was measured over 5 years and compared with performance on nearby unmined land. The study was called the Acland Grazing Trial. This paper evaluates measured key performance indicators of pasture and livestock productivity on the basis of field data from Botanal pasture assessments, cattle weights, and pasture and faecal indicators of diet quality. The paper also draws on performance indicators evaluated in companion papers for soil (Bennett *et al*. 2021), pasture carrying capacity (Paton *et al*. 2021), and economic viability and long-term sustainability modelled using GRASP (Clewett *et al*. 2021).

Materials and methods

Trial site description

The Acland Grazing Trial was conducted from January 2014 until June 2018 on land leased by the Acland open-cut coal mine 15 km north of Oakey (27°S, 151°E). The long-term average annual (summer-dominant) rainfall at Oakey is 659 mm. The enterprise chosen for the trial was growing out young cattle to feedlot entry weight, which was consistent with common commercial land use for the area in the absence of mining. Four paddocks that were sown to pasture were used for the grazing trial and are referred to as the trial paddocks. The paddocks were three rehabilitated sites (Rehab 1, Rehab 2 and Rehab 3) on land that was previously cultivated for crops and then mined, and one unmined site (Control) that was representative of unmined lands in the area, as follows:

- Rehab 1 (22 ha) was the oldest of the rehabilitated sites and was established with sown pasture by 2007
- Rehab 2 (32 ha) was a rehabilitated site and was established with sown pasture by 2010
- Rehab 3 (22 ha) was a rehabilitated site and was established with sown pasture by 2012
- Control (21 ha) was on unmined, previously cultivated land and was sown to pasture with similar species and in the same year as Rehab 3 (i.e. 2012).

During and after mining for coal, the progressive rehabilitation process used by the mine was first to continually dump the fine-grained argillaceous Walloon sandstone inter- and over-burden (mine spoil) on the rehabilitation site until it reached a pre-defined undulating landform, second, to deep rip to ~1 m depth using bulldozers, then to progressively spread the soil removed from mining areas to a target depth of 0.3 m using large bulldozers, and level it using small bulldozers, stick rakes, blades, rippers, offsets, harrows and level bars, and, last, to progressively sow tropical pastures species. Rehabilitation soils in post-mine settings are often nutrient deficient and fertiliser is commonly applied (Mentis 1999; Grigg *et al*. 2000), but fertiliser was not applied here so that comparisons with unfertilised sown pastures on unmined land could be made. In the early years of rehabilitation, soil was stockpiled on top of the dump site before spreading.

The unmined Control paddock was located on a Brigalow Uplands land type (State of Queensland 2019), 3 km from the mine site and Rehab paddocks. The paddock was clear of trees and was used for intensive agriculture (grain and forage crops, dairying) for ~50 years (Carey 2009) before conversion to pasture in 2012. The mine site was also located on lands with a history of intensive agriculture, and, thus, the soil in the Control paddock and the soil recovered during the mining process to top dress the Rehab paddocks are likely to have had similar management histories before mining.

The soil in the Control paddock was a Brown Dermosol (Isbell 2002) representative of Dermosols and Vertosols in surrounding unmined land, and the soil profiles in the Rehab paddocks were classified as Spolic Anthroposols (Bennett *et al*. 2021). Plant-available soil phosphorus (P) in the Control paddock (Colwell P, 0–60 cm, mean 5 mg/kg) was lower than in other unmined sites across the mining lease (mean 23 mg/kg) and the Rehab paddocks (means 29, 35 and 12 mg/kg in Rehab 1, Rehab 2 and Rehab 3 respectively), but was within the ranges measured across those sites. Soil mineral nitrogen (N) supply (defined as the sum of potentially mineralisable N and mineral N, 0–60 cm) was highest in Rehab 2 (12.2 mg/kg) and was lower in the Control (7.9 mg/kg) and Rehab 3 (7.3 mg/kg) paddocks than in Rehab 1 (9.6 mg/kg) or surrounding unmined sites (10.3 mg/kg) throughout the trial. Soil total N and organic carbon in the unmined soils were generally quite low compared with levels in brigalow soils that do not have a long history of cultivation and intensive agriculture. Soil salinity and dispersion were not considered constraints to pasture growth in any of the trial paddock soils. The mine spoil is explored by plant roots and provides a valuable medium to hold water for plant growth.

The two dominant subtropical grass species present at the start of the trial (January 2014) in the unmined Control paddock and in the three Rehab paddocks were Rhodes (*Chloris gayana*) and Bissett creeping blue (*Bothriochloa insculpta* cv. Bisset). Green and Gatton panics (*Megathyrsus maximus* formerly named *Panicum maximum*) were also dominant in the majority of the Rehab 2 paddock and Rhodes and panics dominated Rehab 1. Minor and variable contributions of other grasses, such as Queensland blue grass (*Dichanthium sericeum*) in Rehab 1, pasture legumes and forbs were identified via the pasture observations described below. The pasture species mixes that were sown, and their seed viabilities, are unknown, although commercial mixes of grasses and legumes sown into the Rehab 3 and Control paddocks were most likely to be similar as they were sown in the same year and similar pasture composition was observed at the beginning of the trial in these two paddocks.

Pasture management before commencement of the trial was as follows. All of the Rehab 1 paddock was grazed down to 1500 kg/ha total standing dry matter (TSDM) in late 2011, then rested to accumulate pasture to 2034 kg/ha TSDM in March 2012 when it was grazed for commercial beef production for 47 days at a stocking rate of 2.5 head/ha. Prior to 2011, the land used for the Rehab 1 was not grazed after establishment. The pasture in Rehab 2 and Rehab 3 was not grazed before the trial. By December 2013, the pasture biomass had accumulated to ~5000–6000 kg/ha in Rehab 1, 15 000 kg/ha in Rehab 2 and 6000 kg/ha in Rehab 3. To remove dead and stemmy unpalatable material, the three Rehab paddocks were mechanically slashed to a height of ~30 cm that month. Pasture yield in the unmined Control paddock was also reduced. The paddock was managed with heavy grazing in the months before December 2013 and then rested up to the start of the first trial grazing on 23 January 2014. In mid-January 2014, pasture yields were 3300, 5300, 5000 kg/ha and 1300 kg/ha TSDM in Rehab 1, Rehab 2, Rehab 3 and the Control paddocks respectively. By April 2014, late in the growing season, respective pasture yields were 4590, 6560, 3620 and 4630 kg/ha TSDM, indicating that pasture in the Control paddock had fully recovered from heavy grazing in 2013.

Rainfall observations

Daily rainfall during the trial was recorded by an automatic weather station at the Acland mine office ~2 km from the Rehab paddocks and 5 km from the Control paddock.

Pasture observations

The Botanal technique (Tothill *et al*. 1992) was used to assess pasture yield (as TSDM) and composition in the trial paddocks before each of the 17 grazing periods (Table 1). Information gathered from ~50 quadrat points located in a grid pattern within each paddock and sampling time was as follows:

- Pasture yield (TSDM, kg/ha), species composition (percentage by mass), species frequency of occurrence (presence/absence),
- Percentage of ground covered by green pasture material, organic matter and rock; and
- Proportion of unpalatable pasture (i.e. stemmy pasture material left-over from the previous growing season that stock are unlikely to consume when grazing).

Pasture and land condition ratings were then assigned to each paddock according to the proportion of perennial, productive and palatable ('3P') pasture species present and soil surface condition (Quirk and McIvor 2007; Alexander *et al*. 2018).

Pasture quality was assessed by analysis and calculation of DM digestibility (%), crude protein (CP, %) and metabolisable energy (MJ/kg) of grass leaf samples. The samples were collected from four transects across each trial paddock immediately before each grazing period and were aggregated into one composite sample for each paddock and sampling time. No sample was collected from the Control paddock in Spring 2016 because the pasture was unintentionally crash grazed by 157 head of cattle for 5 days just prior. Prior to analysis, samples were dried at 80°C for 48 h. Analyses were conducted by SGS Australia Pty Ltd using in-house near-infrared reflectance spectroscopy (NIRS) techniques and reference methods from the Australian Fodder Industry Association Inc. (2014) for the in-house NIRS calibrations.

Grazing system

Young cattle, ~300–400 kg average weight, were concurrently grazed in each paddock for short periods of each of the annual seasons when possible. These periods are referred to as trial grazing periods and there were 17 trial grazing periods over the 5 years of the trial (labelled G1–G19, Table 1). Twelve-month grazing years were assumed to start on 8 September (early

Table 1. Grazing periods, pasture and cattle observation dates

Parameter	Year 1 (8 Sep. 2013 – 7 Sep. 2014)				Year 2 (8 Sep. 2014 – 7 Sep. 2015)				Year 3 (8 Sep. 2015 – 7 Sep. 2016)				Year 4 (8 Sep. 2016 – 7 Sep. 2017)				Year 5 (8 Sep. 2017 – 7 Sep. 2018)			
Trial grazing period	–	G1	G2	G3	G5	G6	G7	G8	–	G9	G10	G11	G13	G14	G15	G16	G17	G18	G19	–
Season	Spring 2013	Summer 2014	Autumn 2014	Winter 2014	Spring 2014	Summer 2015	Autumn 2015	Winter 2015	Spring 2015	Summer 2016	Autumn 2016	Winter 2016	Spring 2016	Summer 2017	Autumn 2017	Winter 2017	Spring 2017	Summer 2018	Autumn 2018	–
Cattle entry	–	23 Jan. 2014	16 Apr. 2014	24 June 2014	30 Oct. 2014	14 Jan. 2015	14 Apr. 2015	14 July 2015	–	09 Dec. 2015	08 Mar. 2016	29 June 2016	17 Oct. 2016	31 Jan. 2017	24 Apr. 2017	24 July 2017	13 Nov. 2017	12 Feb. 2018	7 May 2018	–
Cattle exit	–	13 Mar. 2014	28 May 2014	31 July 2014	21 Nov. 2014	17 Feb. 2015	2 June 2015	19 Aug. 2015	–	15 Feb. 2016	26 Apr. 2016	10 Aug. 2016	13 Dec. 2016	17 Mar. 2017	6 June 2017	7 Sep. 2017	15 Dec. 2017	23 Mar. 2018	22 June 2018	–
Number of days	–	49	42	37	22	34	49	36	–	68	49	42	57	45	43	45	32	39	46	–
Faecal sampling	–	–	14 May 2014	8 July 2014	20 Nov. 2014	11 Feb. 2015	1 June 2015	18 Aug. 2015	–	21 Jan. 2016	1 Apr. 2016	1 Aug. 2016	–	17 Mar. 2017	12 May 2017	–	20 Dec. 2017	–	–	–
Botanal sampling	–	14 Jan. 2014	15 Apr. 2014	19 Jun e2014	27 Oct. 2014	14 Jan. 2015	9 Apr. 2015	22 June 2015	–	7 Dec. 2015	16 Mar. 2016	13 June 2016	5 Oct. 2016	23 Jan. 2017	12 Apr. 2017	3 July 2017	1 Nov. 2017	29 Jan. 2018	18 Apr. 2018	–

spring) of each year of the trial. Only three grazing periods occurred in Years 1, 3 and 5 due to seasonal limitations.

The grazing was designed to mimic a rotational grazing system and forage budgets were used to decide stock numbers and the number of grazing days for each rotation. Pasture yields, proportions of unpalatable pasture and anticipated growth (summer growing season only) were used to derive the number of grazing days and numbers of stock required for each trial grazing period and paddock on the basis of 10% utilisation by DM weight of palatable pasture on offer. The aim was to achieve annual stocking rates consistent with the long-term carrying capacity (derived from 30% utilisation of annual pasture growth) to avoid risks of overgrazing and land degradation (McKeon *et al*. 2004; Clewett *et al*. 2021). A second aim was for each trial grazing period to last 6 weeks so as to allow for meaningful weight gain. As a result, trial grazing periods were 6 (±2) weeks, followed by a rest period of 8 (±4) weeks. The rest period was 16 weeks in the dry winter–spring of 2015. All cattle were grazed together on paddocks of sown and native pasture on unmined land during the rest periods. For trial grazing periods during the summer, when significant rainfall and pasture growth was expected, the anticipated 'in grazing' pasture growth was predicted using estimates of long-term seasonal rainfall and pasture rainfall use efficiency, and added to the pasture on offer estimates in the forage budgets. Rehab 3 was over-allocated with stock in G1 due to an overestimation of the size of the paddock. The Control paddock was not grazed in spring 2016 (G13) due to the unintended crash grazing just prior.

In Years 1 and 2, Angus steers and heifers were used in roughly equal numbers and from Year 3 onward, only steers were used. An exception to this was Rehab 3 in G2 of Year 1, which was grazed by steers only. A single herd was used across Years 3 and 4 and consisted of 157 Angus steers bought from a single vendor with an average purchase weight of 235 kg, which was lighter than the previous cohorts. Lighter cattle were used so that the cattle could be kept in the trial for 2 years (i.e. Years 3 and 4) without them becoming too heavy. On arrival, bought cattle were grazed in a single cohort on unmined areas. In Year 5 (2017–2018), Angus steers bred on the Acland pastoral lease were used. At the beginning of each grazing year, animals were randomly allocated to one of the four trial paddocks. Cattle that were outside the preferred weight ranges of 250–350 kg (Years 1, 2 and 5) or 200–325 kg in Year 3, or were surplus to requirements, were defined as 'filler' cattle. The filler group was grazed on the unmined 'rest' paddock. Filler cattle were added into trial cohorts at trial grazing period entry times, when variations to the stocking rate were required.

Cattle were managed in accordance with the Australian Code for the Care and Use of Animals for Scientific Purposes (National Health and Medical Research Council 2013). All cattle were treated with the same treatments, with the exception of animals affected by infectious bovine kerato-conjunctivitis (pink eye), which were treated individually with Terramycin spray when required. Treatments administered to all cattle were 5 in 1 vaccine for clostridial diseases, anthelmintic drench for parasitic worms, and a buffalo fly repellent (Coopers Easy Dose). Throughout the trial, animals were visually monitored and those considered unsuitable for the trial were excluded on the basis that structural or health defects may affect growth rate. Stock water was Class A+ recycled water from the Toowoomba Regional Council's Wetalla wastewater reclamation facility treatment plant and was supplied via a single trough in each trial paddock. Livestock growth promotants and supplementary feeding were not used.

Cattle observations

Cattle liveweights and stocking rates

Cattle were weighed individually at entry and exit of each grazing period. All animals were weighed following a 2.5-h curfew period, with the time between the start of curfew and the end of weighing being 5.5–6 h. Feed and water were withheld from cattle for the full curfew period. Cattle were co-mingled among groups and weighed in random order. The scales were calibrated every 25 animals and tared to zero every 10 animals, if required.

Key performance indicators of cattle production measured were average daily liveweight gain (ADG, kg/head/day), liveweight gain per head of cattle (LWG, kg/head) and liveweight production per hectare. The ADG and LWG per head were calculated using the number of grazing days and the weights of cattle at the entry and exit of each trial and rest grazing period. Cumulative LWG and associated ADG over the periods of grazing the trial paddocks only each year (and excluding gains or losses during rest grazing periods) were calculated using the sum of LWG and days in each trial grazing period and are referred to as trial LWG and trial ADG respectively. Cumulative weight gain that included the rest periods was calculated as the difference in weight per animal between the first and last weighing of each grazing year and is referred to as cumulative LWG. The potential for differences in compensatory weight gains (positive and negative) as cattle moved from trial paddocks to the rest paddock and *vice versa* was examined. Liveweight production per hectare (LWG, kg/ha) was calculated as the product of stocking rate and ADG for each trial grazing period. Cumulative LWG per hectare for the trial grazing periods in each year was calculated as the sum of production per hectare for each trial grazing period and is referred to as trial LWG per hectare.

Stock grazing days (i.e. the product of the number of stock and number of days grazing) per hectare were calculated for each trial grazing period and paddock. Stock numbers were also converted to adult equivalents (AE) using the metabolic weight formula (NRDR 2007) and assuming an AE is a 450 kg steer consuming 9 kg DM/day and gaining ~0.4 kg/day in liveweight.

Faecal and liver analyses

Wet chemistry and NIRS analyses of cattle faecal samples were used to indicate the quality of the diet consumed by the cattle. Samples were collected from each trial paddock at variable times of the day at or around the midpoint of each trial grazing period and/or when feed was not limited (Table 1). Due to resource limitations, no samples were collected in 5 of the 17 trial grazing periods. For each paddock and sample time, cattle were held together and faecal subsamples were collected from just beneath the surface of at least six fresh deposits on the ground, ensuring no contamination with soil, and bulked as a single sample. The samples were kept cool before being sun-dried and delivered to the Symbio Alliance Queensland laboratory for analysis. The faecal P content (% DM) was measured by microwave acid digestion followed by inductively coupled plasma–atomic emission spectroscopy. Faecal NIRS spectra were used to predict the faecal N content (% DM), and the CP content (% DM), non-grass component (% DM) and DM digestibility (DMD, %) of the diet using in-house methods that were based on calibration equations developed by Coates (2004). The ratios of P : N and DMD : CP were also calculated.

Carcase liver samples from the Year 1 cohort of cattle for Rehab 2 (n = 19) were tested for heavy metal contamination. Liver samples were collected at the abattoir on 12 December 2014, stored and transported by road to the Biosecurity Queensland Veterinary Laboratories for analysis of copper, arsenic, cadmium, lead, mercury and zinc concentrations.

Statistical analyses

The trial was a descriptive study over time in four paddocks (Control, Rehab 1, Rehab 2 and Rehab 3) that, due to practical constraints, were not replicated. Therefore, the differences in the management regimes used for each paddock could not be statistically compared. However, internal replication within each paddock enabled calculation of the variance within each paddock and, thus, statistical comparison of paddock means for several pasture and cattle performance indicators. Attribution of direct cause and (paddock) effect based on tests for individual performance indicators was unjustified and was, therefore, excluded. Outcomes of the statistical tests were aggregated as multiple lines of evidence to biologically interpret differences observed among the unreplicated paddocks.

Pasture yield (TSDM, kg/ha) was compared among paddocks over time using restricted maximum likelihood repeated-measures analysis with fixed effect terms of paddock and sample time (trial grazing period), paddocks as subjects, sample times (trial grazing period) as time points and assuming an unstructured autocorrelation model within subject over time. The four transect means of Botanal quadrat yield data within paddocks and sample times were used as internal replicates. Data were transformed using the natural logarithm before analysis.

Statistical summaries and analyses of cattle liveweight performance indicators were conducted on the basis of data from steers that remained in the same trial paddock cohort throughout a grazing year. Heifer data were excluded because there were some significant differences in performance indicators between heifers and steers in Years 1 and 2 (data not shown). Filler cattle were also excluded from the statistical testing. For analysis of rest period data, cattle were grouped according to the paddock they grazed before, and after, the rest period. Mean grazing period entry and exit liveweights, cumulative LWG and ADG per head including and excluding the rest grazing period gains or losses were compared among paddocks for each grazing period (statistical summaries not shown) and year by ANOVA, using cattle within paddocks as internal replicates.

Trends in some cattle and pasture performance indicators over time (sample date) or increasing pasture age (months since sowing, at sample time) were tested using linear regression analysis. Where there was a significant effect of paddock and pasture age but no significant ($P > 0.05$) interaction between the paddock and pasture age, a model was estimated for each paddock using a common slope. The percentage variance accounted for by the regression models, expressed as a proportion, is reported as the 'adjusted R^2' (i.e. R^2 adjusted for the number of model parameters and observations). Cattle LWG was excluded from the regression analysis because of the high inter-annual variability in cattle entry weights. All statistical tests were conducted using Genstat software (19th edn, VSN International Ltd, Hemel Hempstead, UK).

Results

Rainfall

Annual rainfall for Years 1 to 5 of the trial respectively, was 564, 476, 600, 695 and 478 mm and only exceeded the long-term average in Year 4 (2017). Mean annual rainfall was 562 mm during the trial and this was 14% below the long-term average at Oakey. The only seasons that had above average rainfall were autumn 2014 (Year 1), summer 2015 (Year 2), spring 2015 (Year 3) and autumn 2017 (Year 4). Useful autumn rainfall in 2014 and 2017 (Fig. 1) extended the 'green' season and duration of higher cattle LWGs. Winter rain in 2016 promoted the growth of legumes.

Pasture composition and quality

In Rehab 1, Rhodes grass remained dominant throughout the trial (Fig. 2*a*). Green and Gatton panics were initially co-dominant with Rhodes grass, but the yield of the panics declined significantly over time (Table 2). Queensland blue grass, a native grass, maintained a presence as one of the subdominant species. In Rehab 2, green and Gatton panics dominated through the trial period (Fig. 2*b*). Creeping bluegrass was present but at low yields. In both Rehab 3 and the Control paddocks, yields of Rhodes grass declined significantly over time and the yield of creeping blue grass increased significantly (Table 2, Fig. 2*c, d*).

Only in spring (October) 2016 were there significant quantities of legumes (Fig. 3), reaching 21.4%, 10.7%, 11.1% and 4.0% of pasture yield in Rehab 1, Rehab 2, Rehab 3 and Control paddocks respectively. The legumes included vetch (*Vicia* spp.) and medics (*Medicago* spp.), which were sown during pasture establishment, and self-regenerating hexham scent (*Melilotus indica*). In winter and spring 2017, legumes were present but only at levels of 1–4%. At all other samplings, legume content was less than 3% of pasture yield.

Grass leaf samples collected before each trial grazing period showed that Rehab 2 had the highest mean CP levels, and there was little difference among paddocks in the mean metabolisable energy or digestibility over the trial period (Table 3). There was a significant ($P < 0.001$) and similar exponential decline in leaf CP of samples taken in summer and autumn (December to April inclusive) as pasture age (months since sowing) increased across all paddocks (Fig. 4, Table 2).

All pastures were established effectively and were in A pasture and land condition (i.e. best) at the commencement (January 2014) and throughout the trial, maintaining >80% of yield comprising the 3P pasture species at all times. Ground cover was maintained above 80% in all paddocks throughout the trial and was 90% or better on most sampling occasions.

Pasture production

The main differences in the yield (TSDM) of grazed pasture over the trial period were that the yield in the Control paddock was significantly lower than in the other paddocks, and the yield in Rehab 2 was significantly higher than in the other paddocks (Table 3). Rehab 1 and Rehab 3 yields were intermediate and statistically different. These main paddock effects on yield were generally, but not absolutely, consistent across every trial grazing period (Fig. 5).

Rehab 2 maintained the highest yield of grazed pasture throughout the trial, reaching 8236 kg/ha on 16 March 2016 (Fig. 5). Pasture in the Rehab 3 and Control paddocks showed a trend of declining yields with an increase in pasture age over the length of the trial, being consistent with patterns of rundown in pastures. However, natural variation in pasture yields due to seasonal growth patterns and grazing resulted in the slope of the trends being not significantly ($P > 0.05$) different from zero. The first yield point in the Control was

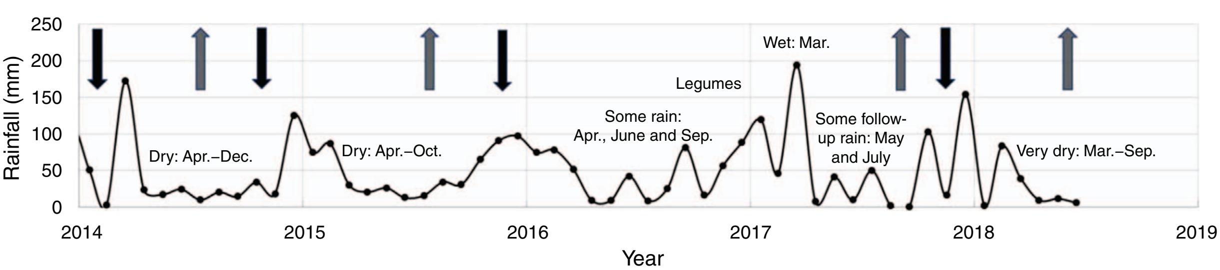

Fig. 1. Monthly rainfall (mm) plotted mid-month and cattle movements at Acland. Text annotations highlight key rainfall features and the period when winter rain in 2016 promoted the growth of legumes. Black downward arrows indicate the start of grazing each year and grey upward arrows indicate the end of grazing each year.

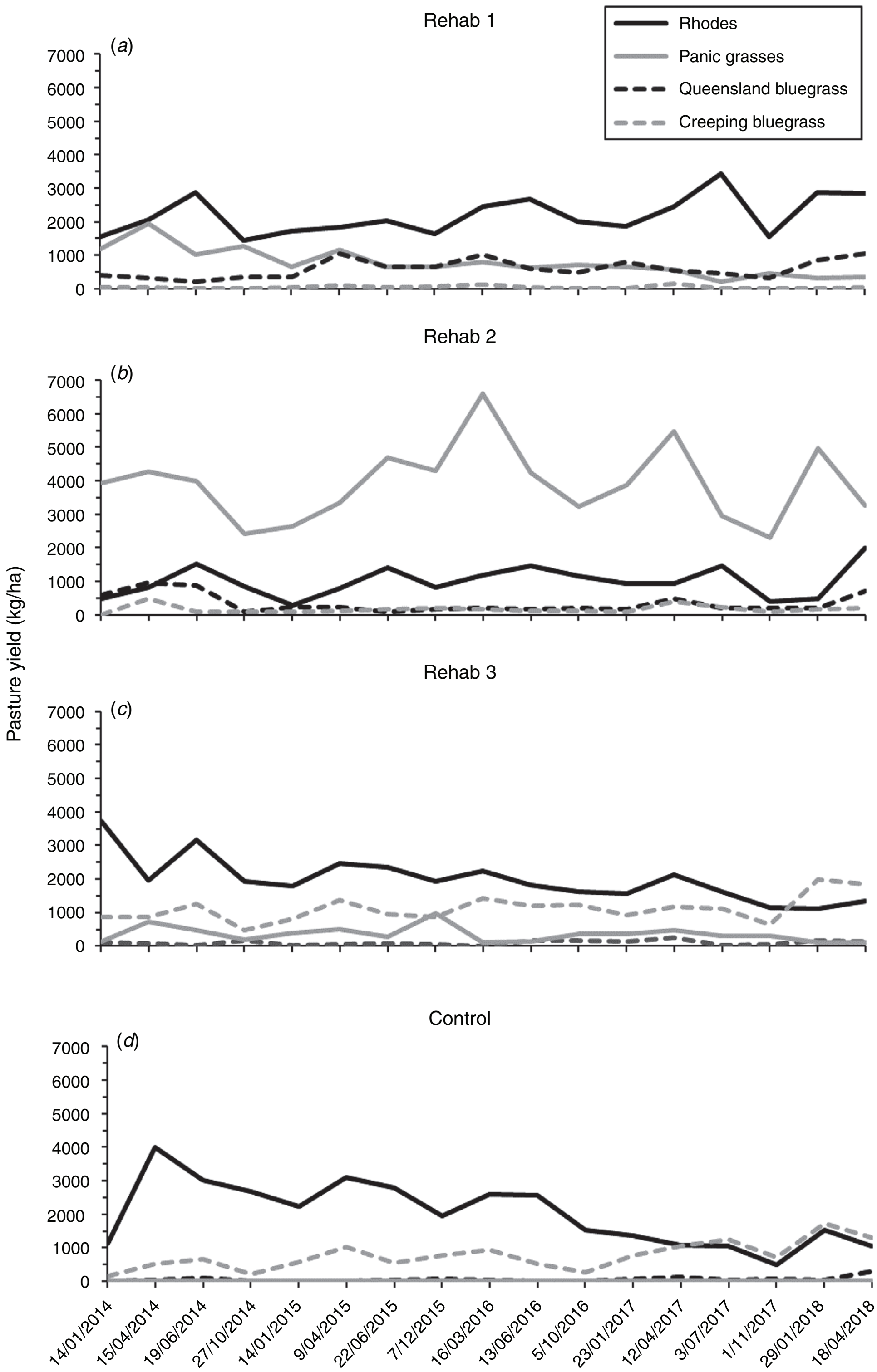

Fig. 2. Pasture yields (total standing dry matter, kg/ha) of the major species Rhodes grass (solid black line), panic grasses (solid grey line), Queensland bluegrass (dashed black line) and creeping bluegrass (dashed grey line) in the (*a*) Rehab 1, (*b*) Rehab 2, (*c*) Rehab 3 and (*d*) Control trial paddocks.

Table 2. Summary of regression models of pasture and cattle key performance indicator changes over time (sample date) or with an increase in pasture age (months since sowing, at sample time) for the Control, Rehab 1, Rehab 2 and Rehab 3 trial paddocks

TSDM, total standing dry matter; DMD, dry-matter digestibility. R^2, R^2-values are adjusted for the number of model parameters and observations. n.s., not significant ($P > 0.05$)

Parameter	Explanatory time variable	Regression trend	P (fitted model)	R^2	Model description for paddocks
		Pasture			
Yield (kg/ha TSDM)	Months since sowing	Decrease	<0.001	0.55	Control, Rehab 3 same slope and constant (one Control outlier removed)
		No change			Rehab 1, Rehab 2
Rhodes (kg/ha)	Sample date	Decrease	<0.05	0.56	Control
		Decrease	<0.001	0.45	Rehab 3
		No change	n.s.	–	Rehab 1, Rehab 2
Panic spp. (kg/ha)	Sample date	Decrease	<0.001	0.64	Rehab 1
		No change	n.s.	–	Control, Rehab 2, Rehab 3
Creeping blue (kg/ha)	Sample date	Increase	<0.05	0.44	Control
		Increase	<0.05	0.20	Rehab 3
		No change	n.s.	–	Rehab 1, Rehab 2
Queensland blue (kg/ha)	Sample date	Increase	<0.05	0.19	Control
		No change	n.s.	–	Rehab 1, Rehab 2, Rehab 3
Leaf crude protein (%)	Months since sowing	Dec.–Apr. data only; decrease	<0.001	0.37	Same slopes, constants Rehab 1, Rehab 2 > Control
		Cattle			
Faecal N (%)	Months since sowing	No change	n.s.	–	–
Faecal P (%)	Months since sowing	Increase	<0.001	0.51	Same slopes, constants Rehab 2, Rehab 3 > Control
Faecal P : N	Months since sowing	Increase	<0.001	0.46	Same slopes, constant Rehab 3 > Control
Predicted diet crude protein	Months since sowing	Decrease	<0.001	0.29	Same slopes, constants Rehab 1, Rehab 2 > Control
Predicted diet DMD	Months since sowing	No change	n.s.	–	–

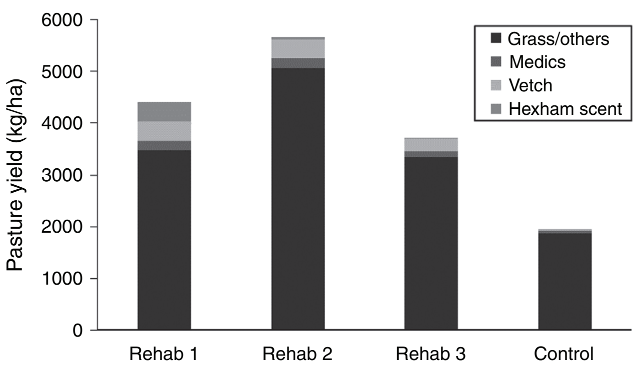

Fig. 3. Yields (total standing dry matter, kg/ha) of grasses and legumes (medics, vetch and hexham scent) in trial paddocks in Spring (October) 2016.

measured in a period of pasture recovery after an unintended crash grazing event in spring 2013, but was lower than photographic records suggest, possibly due to the patchiness of pasture cover at the time adding uncertainty to the Botanal calibration. Taking that point out of the analysis increased the mean grazed pasture yield to 2969 kg/ha TSDM and strengthened the regression model such that the decline was significant ($P < 0.001$) for the Control and Rehab 3 (Fig. 6, Table 2).

Pasture stocking rates

Stocking rates were continually adjusted to achieve a constant grazing pressure across paddocks and years, so that the stocking rate outcomes reflect differences in productivity of the grazing system. Due to a dry season and commensurately

Table 3. Pasture production and grass quality

Pasture yield and grass leaf dry matter crude protein, metabolisable energy and digestibility (mean ± s.d.) over the sampled grazing periods (n) of the trial in each paddock. Pasture yield values in parentheses are back-transformed means predicted by restricted maximum likelihood analysis, with different letters indicating significant ($P < 0.05$) differences among paddock means

Site	n	Pasture yield (kg/ha TSDM)	n	Crude protein (%)	Metabolisable energy (MJ/kg)	Digestibility (%)
Control	17	2871 ± 907.8 (2678a)	16	8.22 ± 3.197	8.19 ± 1.132	59.3 ± 5.88
Rehab 1	17	3965 ± 678.4 (3862c)	17	9.74 ± 2.769	8.32 ± 1.088	60.6 ± 5.75
Rehab 2	17	5656 ± 1343.3 (5340d)	17	12.69 ± 2.885	8.78 ± 1.236	63.4 ± 6.10
Rehab 3	17	3609 ± 739.7 (3491b)	17	9.75 ± 2.723	8.53 ± 0.990	61.8 ± 4.92

short trial grazing periods, in Year 5, cattle grazed the trial paddocks for 117 days, which was fewer days than in all previous years (128 days in Year 1, 141 days in Year 2, 159 days in Year 3 and 190 days in Year 4, Table 4). Cattle grazed the trial paddocks for 48–68% of the total grazing time (i.e. trial plus rest period grazing) each year. Cattle grazed trial or rest pasture for 52%, 80%, 67%, 89% and 61%, and grazed trial pasture only for 35%, 39%, 43%, 52% and 32% of the 12-month grazing year in Years 1–5 respectively.

In Years 3–5 of the trial, there were more grazing days per hectare per year in the Rehab paddocks than in the Control paddock, whereas, earlier, the Control paddock supported more grazing days than did Rehab 1 (Year 1) and similar grazing days to Rehab 3 (Year 2). Over the 5 years, Rehab 2 had the highest trial mean number of grazing days of 160 AE days/ha.year. Rehab 1 and Rehab 3 had 128 and 127 AE grazing days/ha.year respectively, and the Control was lowest with 105 AE grazing days per hectare per year. In G1, Rehab 3 was over-stocked and, consequently, overgrazed due to an overestimation of the size of the paddock. Including that overgraze, but excluding the G13 crash-graze in the Control, the mean annual equivalent stocking rate over the 5 years was highest in Rehab 2 (44 AE/100 ha), lowest in the Control (29 AE/100 ha) and intermediate in Rehab 1 and Rehab 3 (35 AE/100 ha; Table 4).

Cattle LWG

Grazing of the trial paddocks occurred on 46% of days in the trial period from 23 January 2014 to 22 June 2018 (1611 days). The intervening rest periods for each year accounted for a further 33% of days. For the remaining time, there were no cattle on the trial or rest paddocks. ADG was strongly influenced by season (Fig. 7). The ADG was often negative during winter when pasture quality was low after frost and/or new pasture growth was restricted by cold dry weather. Spring and summer ADG were usually maximised in response to rapid pasture growth following rainfall.

There were no significant ($P > 0.05$) differences in entry weights among paddock cohorts for the first grazing period in any year that new cattle were introduced. This reflects successful equal distribution of cattle weights among cohorts at the start of the trial years. Mean cattle entry weights per head were 289 ± 24.8 kg, 334 ± 23.3 kg, 244 ± 30.4 kg and 263 ± 26.0 in Years 1, 2, 3 and 5 respectively. In Year 4, when cattle were carried over from Year 3, the Rehab 2 cohort was heaviest (386 kg/head) and there was no significant difference ($P > 0.05$) in cohort mean entry weight per head among the other three paddocks (Rehab 1 347 kg, Rehab 3 347 kg and Control 363 kg). There were strong positive correlations ($0.81 < r < 0.98$, except for Rehab 3 in Year 2, $0.57 < r < 0.80$), as expected, across all cattle cohorts between cattle entry and exit weights for each of the trial grazing periods.

Over the 5 years of the trial, the trial LWG of cattle grazing the Rehab 2 paddock averaged 98 kg/head (Table 5), compared with 65–75 kg/head in the other paddocks. The 5-year mean cumulative LWG was also highest in Rehab 2 (116 kg/head), where it was 37% higher than the average of the other trial paddocks. The trial and cumulative LWGs in the Rehab 2 cohorts were significantly ($P < 0.05$) higher than in other paddock cohorts in Years 2 (cumulative LWG only), 3 and 5, which included seasons with low rainfall and pasture productivity. Conversely, differences in LWG among paddocks were least pronounced when average productivity was higher (Years 1 and 4), with autumn rains extending the presence of green pastures into winter. Cattle beef production per hectare was also consistently highest in Rehab 2 compared with the other paddocks, with values again being strongly influenced by differences in rainfall and pasture growth, with consequential effects on stocking rates.

There was high LWG of cattle grazing the youngest pastures (Control and Rehab 3) during the first year when leaf N was highest (Fig. 4), and in Year 4, the LWG was high in all paddocks due to favourable rainfall conditions and the growth of legumes. In addition, the LWGs in Year 1 were disrupted during the 4-week rest period between G1 and G2 by 135 mm of rain that occurred over the last week of March. The wet weather was the likely cause of temporary liveweight losses in all paddocks (8 kg/head, on average, and particularly Control 21 kg/head), which was then regained in G2. The high compensatory gain of the Control cohort boosted the trial LWG of the Control for Year 1 that was not reflected in the cumulative LWGs from the start of G1 to the end of G3 (23 January to 31 July 2014; Table 5). Cumulative LWG per head was similar or higher in the Rehab cohorts than in the Control cohort each year.

The trial ADG of Rehab 2 cohort cattle over the 5 years was 0.73 kg/head.day, compared with 0.49, 0.57 and 0.54 in the Rehab 1, Rehab 3 and Control paddocks respectively (Table 5). Rehab 3 cohort cattle performed similarly, or significantly better (G11 and G18, $P < 0.05$), than did Control cohort cattle during the trial grazing periods, except in G1 when the Control cohort outperformed all other paddock cohorts, as previously described (Fig. 7). Cattle in Rehab 1 had a significantly lower ADG than that in the Control cohort in G2, G3, G5, G10, G15 and G17, and Rehab 2 had a significantly lower ADG than did the Control cohort in G5 and G15 only. The seasonal variation within paddocks (the smallest trial grazing period ADG range –0.49 to 1.36 kg/head.day in Rehab 3, and the largest range –0.61 to 1.56 kg/head.day in Rehab 2) was more than double the within-trial grazing period variation among paddocks (smallest range 1.03 to 1.16 kg/head.day, in G13, and largest range 0.79 to 1.56 kg/head.day, in G8), reflecting a strong influence of weather on pasture quality and cattle performance relative to the influence of paddock differences.

For 17 of the 29 trial or rest grazing periods, there were negative correlations (range –0.003 to –0.93) with ADG in the subsequent grazing period for each paddock cohort, suggesting that compensatory weight gains often occurred when cattle moved between the trial and rest paddocks. For example, in the cohorts that suffered the largest weight losses in winter 2018 (Year 5, Control, Rehab 1 and Rehab 3) there were moderate negative correlations ($-0.3 > r < -0.6$) between the positive ADGs during the previous rest period and the negative ADGs in the winter trial period. Cattle with higher rest period growth rates tended to suffer larger weight loss during the subsequent trial grazing period. Across grazing periods and paddocks, there were no other systematic patterns of compensatory weight gains and losses, indicating that the rest paddocks used for the trial were not consistently biasing the measurement of LWG.

Faecal indicators of diet quality

Across the 12 trial grazing periods sampled for faecal indicators of diet quality, there was little difference among trial paddocks in the DMD or the ratio of DMD to CP (Table 6). Similar to grass leaf CP, Rehab 2 had a higher

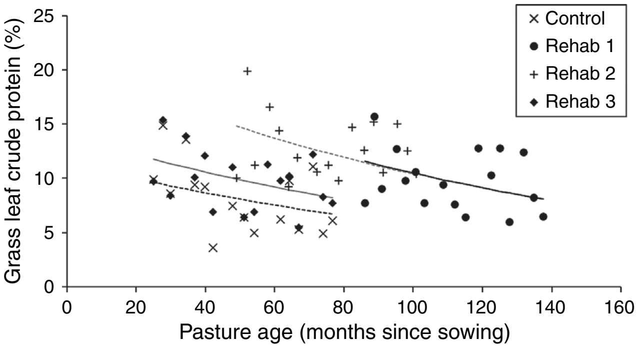

Fig. 4. Grass leaf crude protein versus pasture age (months since sowing) for summer (December to April) sample dates with fitted predicted exponential decline regression models for the Control (black dashed line; Leaf crude protein% = $11.508 \times \exp^{(-0.007 \times \mathrm{age\_mo})}$), Rehab 1 (black solid line; Leaf crude protein% = $21.1 \times \exp^{(-0.007 \times \mathrm{age\_mo})}$), Rehab 2 (grey dashed line; Leaf crude protein% = $20.9 \times \exp^{(-0.007 \times \mathrm{age\_mo})}$), and Rehab 3 (grey solid line; Leaf_protein% = $14.0 \times \exp^{(-0.007 \times \mathrm{age\_mo})}$) paddocks. The linear regression constants of ln-transformed data were significantly higher for Rehab 1 and Rehab 2 than for the Control, and the constant for Rehab 3 was not significantly different from the Control constant. The overall model, with a common slope was significant ($P < 0.001$, adjusted $R^2 = 0.37$).

Fig. 6. Mean pasture yield (total standing dry matter, kg/ha TSDM) versus pasture age for the Rehab 3 and Control paddocks, showing fitted predicted exponential decline regression models with one Control point (asterix) removed. Fitted model ($P < 0.001$, adjusted $R^2 = 0.55$) equations for Control yield_kg/ha = $5437 \times \exp^{(-0.01236 \times \mathrm{age\_mo})}$ (black dashed line), and Rehab 3 yield = $4770 \times \exp^{(-0.0059 \times \mathrm{age\_mo})}$ (grey solid line). The slopes and constants for Control and Rehab 3 were not significantly ($P > 0.05$) different from each other. The fitted slopes for Rehab 1 and Rehab 2 were not significant ($P > 0.1$) and the data are therefore not presented.

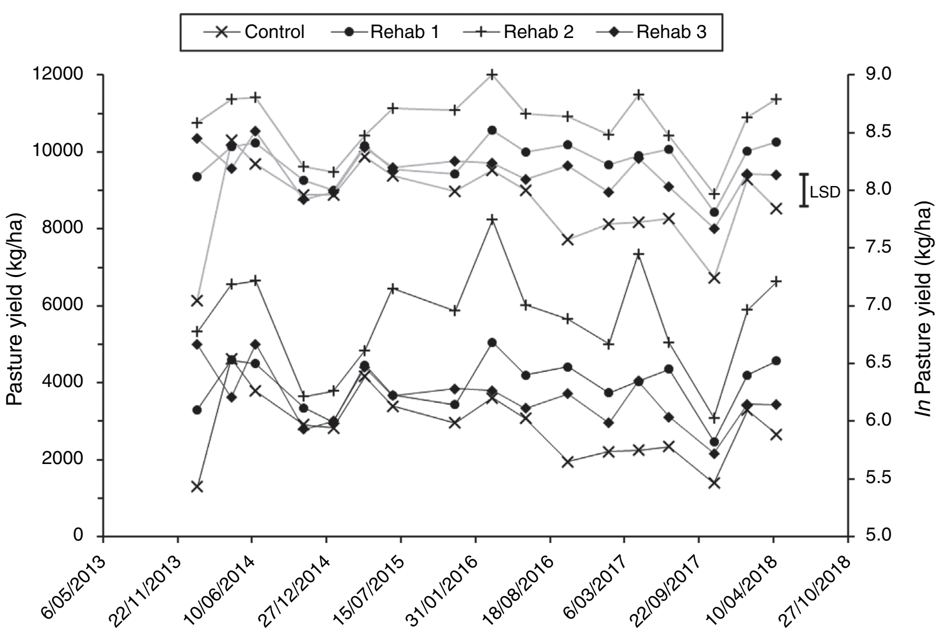

Fig. 5. Pasture yield (black lines, total standing dry matter (TSDM), kg/ha) and transformed predicted mean pasture yield (grey lines, lnTSDM, kg/ha) for Rehab 1, Rehab 2, Rehab 3 and Control paddocks between January 2014 and April 2018. The l.s.d. (5%) of the transformed data for most pair-wise sample time × paddock comparisons (0.275) are shown. The l.s.d. for pairwise comparisons in G3 of Rehab 1, 2 and 3 against all other paddocks, and in G13 for the Control paddock against all other paddocks was 0.337.

Table 4. Number of days stock remained in paddocks during trial, rest and ungrazed (when cattle were not observed) periods, number of head per paddock and per hectare, stocking rate as adult equivalent (AE) per 100 ha, and head and adult equivalent grazing days per hectare for each grazing period and trial site cohort

Annual (12-month) equivalent means are shown for stocking rates

Grazing period	Days	Control					Rehab 1					Rehab 2					Rehab 3				
		Head	Stocking rate (Head/ha)	Stocking rate (AE/100 ha)	Grazing days (Grazing days/ha)	Grazing days (AE grazing days/ha)	Head	Stocking rate (Head/ha)	Stocking rate (AE/100 ha)	Grazing days (Grazing days/ha)	Grazing days (AE grazing days/ha)	Head	Stocking rate (Head/ha)	Stocking rate (AE/100 ha)	Grazing days (Grazing days/ha)	Grazing days (AE grazing days/ha)	Head	Stocking rate (Head/ha)	Stocking rate (AE/100 ha)	Grazing days (Grazing days/ha)	Grazing days (AE grazing days/ha)
Year 1																					
G1	49	20	0.95	74	47	36	20	0.91	67	45	33	40	1.25	94	61	46	40[B]	1.82	134	89	65
G2	42	25	1.19	97	50	41	20	0.91	73	38	31	40	1.25	102	53	43	20	0.91	74	38	31
G3	37	20	0.95	84	35	31	25	1.14	98	42	36	37	1.16	102	43	38	23	1.05	90	39	33
Trial	128	22	1.03	85	132	109	22	0.98	80	125	100	39	1.22	99	157	127	28	1.26	99	166	130
Rest	61																				
Ungrazed	176																				
Annual equivalent	365		0.36	30				0.34	27				0.43	35				0.45	36		
Year 2																					
G5	22	20	0.95	74	21	16	23	1.05	80	23	18	36	1.13	86	25	19	20	0.91	72	20	16
G6	34	18	0.86	75	29	26	22	1.00	86	34	29	35	1.09	95	37	32	20	0.91	81	31	28
G7	49	20	0.95	89	47	44	20	0.91	88	45	43	30	0.94	90	46	44	20	0.91	88	45	43
G8	36	20	0.95	90	34	32	22	1.00	94	36	34	35	1.09	108	39	39	20	0.91	88	33	32
Trial	141	20	0.93	82	131	118	22	0.99	87	138	124	34	1.06	95	147	134	20	0.91	82	128	118
Rest	152																				
Ungrazed	72																				
Annual equivalent	365		0.36	32				0.38	34				0.40	37				0.35	32		
Year 3																					
G9	68	20	0.95	66	65	45	23	1.05	72	71	49	46	1.44	99	98	67	25	1.14	76	77	52
G10	49	27	1.29	101	63	50	32	1.45	113	71	55	63	1.97	157	96	77	35	1.59	119	78	59
G11	42	20	0.95	71	40	30	21	0.95	71	40	30	38	1.19	92	50	39	20	0.91	67	38	28
Trial	159	22	1.06	79	168	124	25	1.15	85	182	134	49	1.53	116	244	183	27	1.21	87	193	138
Rest	86																				
Ungrazed	121																				
Annual equivalent	366		0.46	34				0.50	37				0.67	50				0.53	38		
Year 4																					
G13	57	157[A]	A	A	37[A]	30[A]	16	0.73	66	41	38	26	0.81	76	46	43	16	0.73	64	41	37
G14	45	20	0.95	96	43	43	25	1.14	114	51	51	39	1.22	128	55	57	21	0.95	95	43	43
G15	43	13	0.62	71	27	30	23	1.05	117	45	50	47	1.47	171	63	73	22	1.00	110	43	47
G16	45	11	0.52	62	24	28	20	0.91	106	41	48	34	1.06	131	48	59	15	0.68	79	31	36
Trial	190	15	0.70	76	93	101	21	0.95	101	178	187	37	1.14	126	212	233	19	0.84	87	158	162
Rest	135																				
Ungrazed	40																				
Annual equivalent	365		0.25	28				0.49	51				0.58	64				0.43	44		
Year 5																					
G17	32	14	0.67	47	21	15	20	0.91	63	29	20	36	1.13	80	36	26	19	0.86	61	28	20
G18	39	20	0.95	79	37	31	25	1.14	92	44	36	48	1.50	125	59	49	22	1.00	83	39	32
G19	46	14	0.67	57	31	26	21	0.95	82	44	38	40	1.25	111	58	51	18	0.82	71	38	33
Trial	117	16	0.76	61	89	72	22	1.00	79	117	94	41	1.29	105	152	125	20	0.89	72	104	85
Rest	104																				
Ungrazed	144																				
Annual equivalent	365		0.24	20				0.32	26				0.42	34				0.29	23		
All years																					
Trial total					613	524				741	639				912	802				750	633
Trial mean	147	19	0.90	77	123	105	22	1.02	86	148	128	40	1.25	108	182	160	23	1.02	86	150	127
Annual equivalent			0.34	29				0.41	35				0.50	44				0.41	35		

[A]The Control fence was broken and 157 head grazed the paddock for 5 days. Not included in weight gain data, but included here for completeness. Weights of 13 filler cattle that were returned to the Control for G14 were used for annual weight gain comparisons. The annual equivalent mean stocking rate, including the crash grazing stock data for the G13 period, was 0.36 head/ha for both Year 4 and over all 5 years. [B]Overgrazing of Rehab 3 due to incorrect estimate (37 ha) of actual paddock size (22 ha).

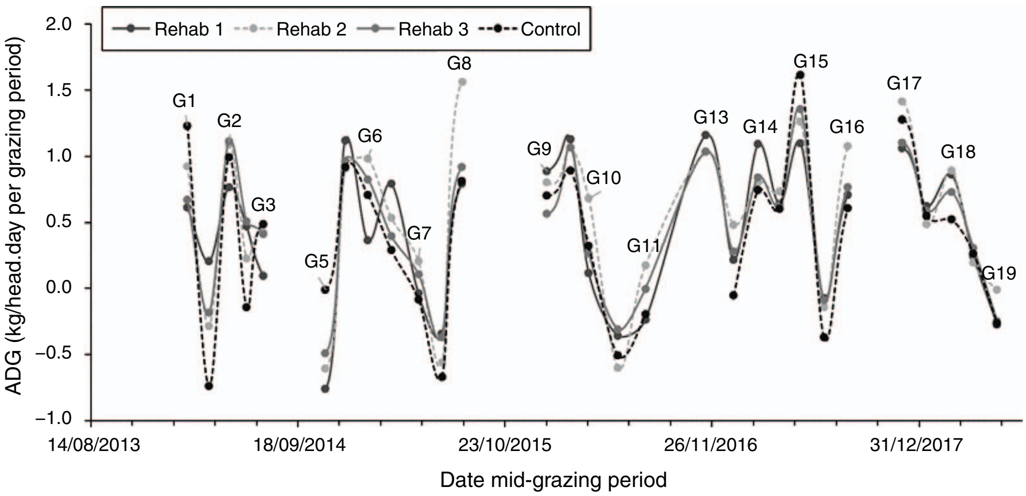

Fig. 7. Average daily growth (ADG, kg/head.day per grazing period) for cattle grazing the Rehab 1, Rehab 2, Rehab 3 and Control paddocks over time. Points include trial grazing periods (labelled) and rest grazing periods.

Table 5. Mean (±s.d.) liveweight gain per head (trial LWG per head, kg/head), average daily liveweight gain per head (trial ADG, kg/head.day) and liveweight gain per hectare (trial LWG per hectare, kg/ha) during trial grazing periods only, and cumulative liveweight gain per head from the first to last grazing period, for each paddock cohort of cattle and year of the trial

Five-year means and the number of steers that remained in the same trial paddock cohort throughout each annual cycle for which data were available (*n*) are also presented. Mean LWG excluding G1 is reported in parentheses for Year 1. Means for Year 4 and All years exclude G13, because the Control paddock was not grazed in spring 2016 (G13) due to an unintended crash grazing event immediately prior. Some LWG means that include G13 are reported in parentheses. The sum of number of days grazing was constant within year, so the statistical differences were the same for trial ADG and trial LWG per head means. Values followed by different letters are significantly ($P < 0.05$) different among paddock cohorts within a year

Paddock	Year 1	Year 2	Year 3	Year 4	Year 5	All years
			n			
Control	10	7	19	7	13	56
Rehab 1	10	11	16	10	18	65
Rehab 2	18	9	25	17	36	105
Rehab 3	11	7	9	9	18	54
			Trial LWG per head (kg/head)			
Control	121 ± 21.1c (56b)	49 ± 24.8b	56 ± 17.1a	130 ± 32.9a (–)	49 ± 14.6a	74 ± 39.2
Rehab 1	66 ± 12.8a (36a)	22 ± 15.1a	56 ± 18.0a	128 ± 28.5a (194a)	55 ± 18.0a	65 ± 35.9
Rehab 2	108 ± 16.4c (59b)	85 ± 36.3c	95 ± 26.3b	139 ± 27.8a (198a)	79 ± 16.4b	98 ± 31.1
Rehab 3	95 ± 13.6b (62b)	55 ± 22.7bc	51 ± 20.1a	131 ± 26.6a (190a)	52 ± 18.2a	75 ± 36.2
			Cumulative LWG per head (kg/head)			
Control	89 ± 16.3ab	91 ± 20.9a	43 ± 15.6a	136 ± 19.2a (–)	94 ± 17.3a	81 ± 34.6
Rehab 1	85 ± 11.3a	112 ± 15.5b	58 ± 17.1a	149 ± 18.3a (226a)	103 ± 17.2a	97 ± 34.0
Rehab 2	102 ± 16.8b	141 ± 23.9c	80 ± 27.8b	160 ± 26.5a (242a)	117 ± 21.4b	116 ± 35.2
Rehab 3	102 ± 21.1b	114 ± 8.3b	55 ± 25.3a	151 ± 22.8a (223a)	101 ± 14.7a	103 ± 34.0
			Trial ADG per head (kg/head.day)			
Control	0.95 ± 0.166	0.35 ± 0.177	0.35 ± 0.107	0.98 ± 0.248	0.42 ± 0.125	0.54 ± 0.309
Rehab 1	0.51 ± 0.100	0.15 ± 0.107	0.35 ± 0.113	0.96 ± 0.214	0.47 ± 0.153	0.49 ± 0.276
Rehab 2	0.84 ± 0.128	0.61 ± 0.258	0.60 ± 0.165	1.05 ± 0.209	0.68 ± 0.140	0.73 ± 0.231
Rehab 3	0.74 ± 0.107	0.39 ± 0.161b	0.32 ± 0.126	*0.98 ± 0.200*	0.45 ± 0.155	0.57 ± 0.277
			Trial LWG per hectare (kg/ha)			
Control	124	44	58	89	39	71
Rehab 1	61	21	62	134	57	67
Rehab 2	132	91	153	175	102	131
Rehab 3	118	50	64	118	50	80

Table 6. Faecal indicators of diet quality (mean ± s.d.) over the trial period for cohorts from each trial paddock
Means are for one composite faecal sample per paddock across the sampled grazing periods (*n*). DMD, dry matter digestibility; N, nitrogen; P, phosphorus

Paddock	*n*	Diet crude protein (%)	Diet non-grass (%)	Diet DMD (%)	Diet D MD : crude protein	Faecal N (%)	*n*	Faecal P (%)	Faecal P : N
Control	12	7.3 ± 1.20	4 ± 3.8	56.2 ± 3.64	8 ± 1.5	1.5 ± 0.13	12	0.31 ± 0.061	0.27 ± 0.07
Rehab 1	12	7.5 ± 1.27	7 ± 6.4	56.5 ± 3.65	8 ± 1.6	1.5 ± 0.12	10	0.54 ± 0.107	0.48 ± 0.12
Rehab 2	12	9.3 ± 2.08	13 ± 4.1	58.0 ± 2.92	7 ± 1.5	1.7 ± 0.14	12	0.68 ± 0.212	0.48 ± 0.20
Rehab 3	12	7.9 ± 1.62	8 ± 6.2	56.6 ± 4.44	7 ± 1.4	1.5 ± 0.18	12	0.48 ± 0.181	0.40 ± 0.20

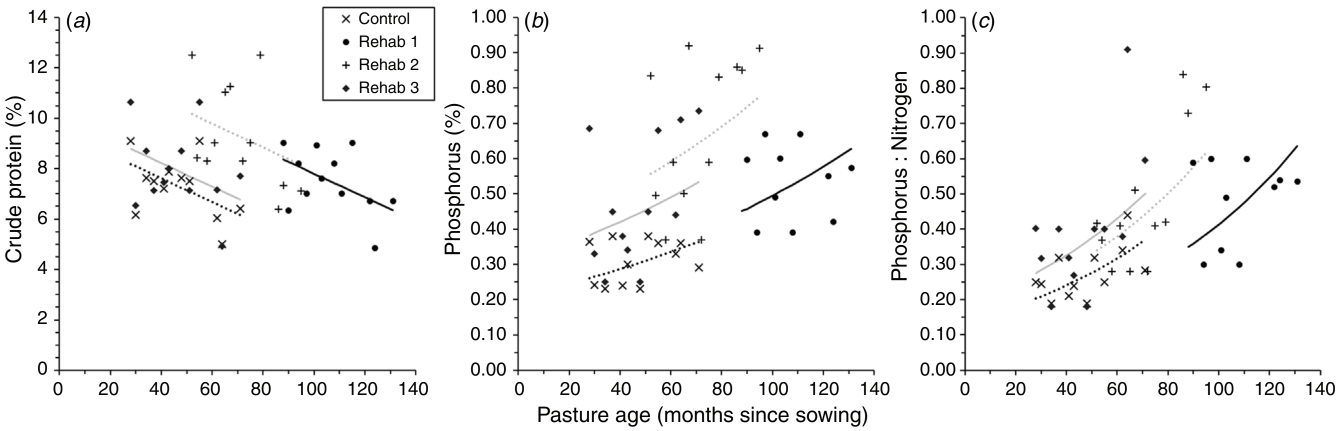

Fig. 8. Faecal indicators of (*a*) dietary crude protein, (*b*) faecal phosphorus percentage and (*c*) faecal phosphorus:nitrogen ratio versus pasture age (months since sowing) in each trial paddock, showing fitted predicted regression models (Control; black dashed line, Rehab 1; black solid line, Rehab 2; grey dashed line, Rehab 3; grey solid line). Regression equations were (*a*) Crude protein% (Control) = –0.047 × Pasture age + 9.5, Rehab 1 constant = 12.5, Rehab 2 constant = 12.6, Rehab 3 constant = 10.1 ($P < 0.001$, adjusted $R^2 = 0.29$), (*b*) Phosphorus% (Control) = 0.211 × $\exp^{(0.0077 \times \text{age\_mo})}$, Rehab 1 constant = 0.229, Rehab 2 constant = 0.373, Rehab 3 constant = 0.309 ($P < 0.001$, adjusted $R^2 = 0.51$), (*c*) P:N (Control) = 0.138 × $\exp^{(0.0139 \times \text{age\_mo})}$, Rehab 1 constant = 0.103, Rehab 2 constant = 0.165, Rehab 3 constant = 0.187 ($P < 0.001$, adjusted $R^2 = 0.46$).

predicted dietary CP (9.3%) than did the other paddocks (7.3–7.9%). Rehab 2 also had a higher predicted non-grass diet content (13%) than did the other paddocks (4–8%), and a higher percentage of faecal N (1.7%) than did the other paddocks (1.5%). The percentage of faecal P was also higher in Rehab 2 (0.68%) than in the other Rehab paddocks (0.48–0.54%) and the Control (0.31%). The faecal P:N ratio was lower in the Control (0.27%) than in Rehab 1 and Rehab 2 (both 0.48%), but was more similar to that in Rehab 3 (0.40%).

General trends in faecal indicators with an increase in pasture age (months since sowing) were that the predicted diet CP decreased across all paddocks, the P content and the P:N increased across all paddocks, and there was no change ($P > 0.05$) in faecal N percentage and predicted diet DMD (Fig. 8, Table 2). Grouping paddocks as Control with Rehab 3 and Rehab 1 with Rehab 2 only (marginally) improved the linear regression model for diet CP.

Liver heavy metals

Of the 19 cattle livers tested for heavy metal contamination in Year 1, only one sample had a copper concentration (103.0 mg/kg) that was higher than the normal range for cattle of all ages (25–100 mg/kg). The other 18 samples had heavy metal concentrations within the normal ranges, indicating that heavy metal contamination was not a concern for the Rehab 2 cohort.

Discussion

Challenges of the trial procedures

The trial procedures used presented several expected and unexpected challenges. First, the trial treatments (i.e. age of rehabilitated or unmined sown pasture) could not be replicated. To account for this, statistical comparisons between paddock populations of cattle and pasture attributes were conducted using within-paddock variation as pseudo-replication. The paddock-level statistical comparisons provided insight into differences and similarities among the paddock-level grazing systems, and differences among paddocks could not be attributed to any single element of the grazing system, such as pasture age. A rehabilitation study by Pauw *et al.* (2018) was similarly affected by a pseudo-replication constraint, which they acknowledged could overestimate the statistical significance of treatment differences. The lack of replication of the Control paddock was mitigated through analyses in three parallel studies. Detailed assessments of the soil and pasture characteristics of the Control paddock were compared with those in surrounding unmined land (Bennett *et al*. 2021; Paton *et al*. 2021), and productivity comparisons of the grazing system were assessed through modelling and simulation studies (Clewett *et al*. 2021). Key findings of these parallel studies are highlighted in the present study. Importantly, soil fertility and pasture growth characteristics (Paton *et al*. 2021) of the Control paddock were within ranges measured on surrounding unmined land, so the Control paddock was considered a representative comparison in the present study.

A second challenge was that the trial grazing periods were necessarily short relative to total grazing days (48–68% of total grazing days). The effects of the trial paddocks on LWG were, therefore, somewhat diluted (i.e. a low signal to noise ratio) by both effects of the communal 'rest' period grazing and by any periods of compensatory gain or loss on re-entry to the trial paddock. Increasing the number of days grazing the trial paddocks in proportion to the total number of grazing days increases the potential for trial paddock, rather than rest paddock, effects to be measured via cattle weight gains and losses. However, an increase in this proportion would have compromised the sustainability criteria of the forage budget that underpinned the grazing system. Third, the number of cattle 'always in group' was reduced by unintentional swapping during weighing and this reduced the statistical power of comparisons among cattle cohorts for each grazing period. However, in terms of stock numbers, Griffiths and Rose (2017) suggested that stocking rates of no fewer than 10 head per site be used for grazing system studies. Their benchmark was achieved in the present study, with the minimum herd sizes being 11 (G16), 16 (G13), 26 (G13) and 15 (G16) in the Control, Rehab 1, Rehab 2 and Rehab 3 paddocks respectively.

A fourth challenge was that the effect of season on pasture productivity and LWG was far greater than any paddock effect and the periodic grazing regime did not fairly represent all seasons. Monthly analysis of days grazing showed that observations in spring were relatively few compared with summer and autumn. However, the trial did provide opportunities to study the effect of treatment under a range of seasonal scenarios, and the trends were largely consistent across exceptionally dry (e.g. G11), average moisture (e.g. G9), wetter than average (G13) and frosty (G8) conditions. A fifth challenge was the unplanned crash grazing event that occurred before the spring graze in 2016 (G13) on the Control paddock. The Control cohort was, therefore, retained in the rest paddock for that grazing period. The Control cohort was examined for their ADG during this period to assess any possible bias. The bias was in favour of the unmined land whereby the Control cohort outperformed the Rehab cohorts for G13. This allowed fair inclusion of the Control for direct comparison during G14 through G16 grazing. Another consideration was that there were no heifers in the Rehab 3 cohort in G2, but this was unlikely to have biased the cattle performance indicators in favour of Rehab 3, because there were no significant differences in ADG between heifers and steers in the other paddock cohorts during G2, or in any paddock cohort during the other trial grazing periods of that grazing year (G1 and G3; data not shown). A further challenge was that the short-term (5-year) observation period did not allow sufficient time for full expression of pasture responses in yield, composition and quality and consequential livestock responses of diet selection and LWG.

The challenges faced by the present study are not peculiar to this grazing system study. The Wambiana grazing trial, established in 1997 in northern Queensland, demonstrated the value of long-term data to prevent overly good or overly poor weather and other factors adding bias to short-term outcomes (O'Reagain *et al*. 2014). Griffiths and Rose (2017) also experienced some of the issues in their project in which data were recorded over 2 years and 9 months, with two periods of set stocked grazing. Fortunately, the 5-year Acland Grazing trial with 17 trial grazing periods and spatially intensive within-paddock assessments provided opportunities to (a) study a range of seasonal scenarios, (b) statistically compare paddocks, and (c) calibrate and, subsequently, use the GRASP model to estimate mean annual pasture and cattle productivity. The modelling overcame the bias in the observed values caused by the absence of several grazings. An ongoing pasture and cattle monitoring regime would also help address these queries.

Differences in pasture yields, stocking rates and LWGs among the trial paddocks

Up to a 50% difference among paddocks in mean cumulative LWG per head (Table 5) was magnified by up to almost 100% difference among paddocks in pasture growth supporting up to 44–48% difference in stock grazing days and stocking rate (Table 4), resulting in up to almost 100% difference in LWG per hectare (Table 5). Rehab 2 (the second-oldest pasture) had the equal highest or highest cattle growth rates per head and per hectare each year. Except in Year 1 when Rehab 3 was overgrazed in G1, Rehab 2 also had commensurately higher stock grazing days than the other trial paddocks. Rehab 2 also had the highest grass leaf CP concentrations on most occasions during the trial and higher dietary CP predicted from faecal samples than did the other paddocks, both of which provide good evidence that the high cattle performance observed was attributable to diet quality as well as pasture quantity. The unmined Control paddock performed most similarly with regard to some pasture and cattle performance indicators (species composition, legume content in spring 2016, leaf CP over time, N uptake, pasture yield, grazing days per hectare, cumulative LWG per head, faecal P) to the Rehab 3 paddock sown in the same year, and for other performance indicators (leaf CP and metabolisable energy, LWG per hectare, dietary CP predicted from faecal samples) to the Rehab 1 pasture.

The differences in pasture yield (TSDM) among the trial paddocks were similar to differences in pasture growth observed in the absence of grazing in the trial paddocks (Paton *et al*. 2021). Observed differences in pasture yield and cattle production performance indicators were also reflected well by annual-equivalent parameters predicted by GRASP model simulations for the trial and long-term periods using the same livestock numbers, weights and periodic grazing regime as the present study (Clewett *et al*. 2021). The modelling estimated a mean utilisation of 28% of annual pasture growth across all paddocks over the trial period. Utilisation in the Control paddock (31%) was higher than the mean and this higher rate was likely to have provided a marginal increase in the observed cumulative LWG per hectare from the Control.

The differences in pasture productivity among paddocks were not attributed to differences or changes in the land condition of the paddocks, given all paddocks remained in A condition throughout the trial. Differences in pasture productivity were instead more likely a result of initial soil fertility levels and pasture rundown (see next discussion section). The good performance of cattle grazing the rehabilitated paddocks relative to the Control paddock also inferred that there were no major adverse stress-related impacts of the mining operations on the productivity of the Rehab cattle. This inference was supported by a separate study at the New Acland mine site in 2017–2018 (Newsome 2018). Over 6 weeks, Newsome (2018) found that there was no significant difference in stress-related indicators between cattle grazing adjacent to the mine versus those grazing at a relatively quiet location 5.6 km from the mine. The stress indicators assessed were weight gain, distance travelled per day, grazing distribution and preference within the paddocks, ultimate pH and meat colour of the meat post-slaughter. Explanatory variables measured were noise and dust levels. Further to this, hind-casting of noise that was likely to have occurred at the Acland coal mine over the 2014–2018 period (SLR Consulting 2018) suggests that there would also have been no adverse impact on the trial cattle reported in the present study.

Influence of soils and pasture rundown on paddock productivity

Soil fertility levels are affected by management and by inherent soil properties. The Control paddock had a history of cultivated cropping and was on a Brigalow Uplands land type derived from Walloon sandstones. Soils on this land type typically have low fertility (Bennett *et al*. 2021). As a consequence, the Control paddock soil was nutrient-depleted and pasture and cattle productivity was not expected to be high. A challenge of the land condition rating system is that the pasture and soil features that are assessed do not necessarily account for soil fertility constraints imposed by a prior history of cultivation.

The soil in the Rehab paddocks was also likely to have had a history of cultivation but with different inherent soil fertility. Small areas of reasonably fertile Basaltic Uplands softwood scrub soils may have been used for Rehab 1 and Rehab 2 (Paton *et al*. 2021). The faecal P content results were fairly consistent with the soils data, in that there was low faecal P in the Control and higher faecal P in Rehab 2. Similar to many pasture and cattle performance indicators, there was also evidence that, of the rehabilitated pastures, Rehab 3 had the soil properties most similar to those of the unmined Control paddock (Bennett *et al*. 2021). Bennett *et al*. (2021) suggested that the Rehab 3 soil possibly also originated from low-P Brigalow Uplands soils. Rehab 3 was, therefore, probably the most analogous rehabilitated pasture to the surrounding Brigalow landscape and more representative than Rehab 1 or Rehab 2 of the remainder of the rehabilitated land at the Acland coal mine. The productivity of Rehab 3 was therefore considered more relevant to future rehabilitation planning at the mine than were the productivities of Rehab 1 or Rehab 2.

The disturbance of soil that occurs when pasture is sown promotes the mineralisation of soil organic matter, leading to higher availability and uptake of plant nutrients (Myers and Robbins 1991) and a lift in pasture productivity. After an initial lift, productivity often declines as pastures age and the process is known as rundown. Symptoms of rundown have been observed in many sown grass pastures in northern Australia (Graham *et al*. 1981; Robbins *et al*. 1987; Myers and Robbins 1991; Peck *et al*. 2011). Rundown is mostly due to mineral N being incorporated into increasing amounts of organic matter, thus reducing the residual amount of soil mineral N available for plant growth. There was some evidence of pasture rundown with an increase in pasture age on both the rehabilitated and unmined paddocks in the present study (Table 2); pasture yields decreased in the Rehab 3 and Control paddocks (but remained high in Rehab 1 and Rehab 2 for the duration of the trial), and grass leaf CP and dietary CP predicted from faecal analysis decreased in all four trial paddocks. Pasture N yields (uptake) also decreased in ungrazed pasture plots in the Control, Rehab 2 and Rehab 3 paddocks (Paton *et al*. 2021). Pasture N yields in Rehab 2, in particular, declined markedly from 77 kg/ha in May 2014 to 17.5 kg/ha in April 2018.

Pasture composition often changes in response to pasture rundown (Burrows 2001; Peck *et al*. 2011). Composition changes observed in the trial paddocks support the apparent trends in rundown seen in yield and quality data. In the Rehab 3 and Control paddocks, the yield of N-demanding Rhodes grass declined and the yield of creeping blue grass increased to become co-dominant with Rhodes grass by the end of the trial. Bissett creeping bluegrass survives and competes well at lower soil fertility levels (McIvor 1984; Partridge *et al*. 2009). Conversely, and consistent with high soil fertility, high fertility-demanding green and Gatton panic grasses dominated pasture composition in Rehab 2 throughout the trial, despite declining pasture N yields. There was no significant change in pasture yield of Rehab 1 (Fig. 5), but both green and Gatton panics declined quickly, perhaps due to selective grazing of the highly palatable species, especially where it grew in small areas of possibly higher fertility soil in a larger paddock. Supporting this theory, Bennett *et al*. (2021) found that Colwell P ranged from 35 to 72 mg/kg between transects over time in Rehab 1 and from 26 to 123 mg/kg in Rehab 2, and they observed patches of panic species between some soil sampling sites.

Pasture rundown can commensurately constrain production from grazing livestock, with decreases in annual LWG of 7–9 kg/head.year being measured over periods of 5–8 years in central and south-eastern Queensland (Robbins *et al*. 1986; Radford *et al*. 2007). Trends in observed LWG over time were not able to be assessed in the present study due to annual changes in the entry weights of the trial cattle. However, GRASP model simulations estimated that the net impact of productivity lift and rundown was a contribution of an extra 14% to LWGs (kg/ha), on average, across all paddocks during the 5-year trial period (Clewett *et al*. 2021).

For the productivity indicators and paddocks for which rundown was observed, the rates of rundown (reflected by regression slopes in Table 2) were similar among paddocks. However, the extent of rundown observed over the trial period varied among paddocks and was seemingly dependent on both the pasture age and the initial soil fertility. Clewett *et al*. (2021) estimated the net lift in pasture growth across paddocks by using rundown rates as a function of pasture age and N fertility. After subtracting the net lift in growth (~45, 1200, 734 and 500 kg/ha.year TSDM for Rehab 1, Rehab 2, Rehab 3 and the Control paddocks respectively) from the estimated 5-year means, pasture growth in its fully rundown state was estimated as ~4500, 6300, 3600 and 3000 kg/ha.year for the respective paddocks. High soil fertility (Rehab 1 and Rehab 2) appeared to have a larger positive impact on pasture growth, than more recent sowing (Rehab 3 and Control). Soil fertility was, therefore, considered to be the most important driver of observed differences in performance indicators among the paddocks.

The viability of beef production from rehabilitated lands and unmined lands in the brigalow region

Viability of beef production is influenced by the productivity and profitability of a grazing system and by the market acceptability of the product. In terms of market acceptability, the few data collected on the heavy metal content of livers from cattle grazing the Rehab 2 rehabilitated pasture suggest that the Rehab meat was likely to be considered safe by consumers. Testing of meat quality attributes such as meat chemical composition and taste acceptability is warranted to further identify the market acceptability of meat products from cattle grazing rehabilitated pasture.

The pasture productivity of the trial paddocks compared favourably with ungrazed sites on a commercial grazing property of the Darling Downs region (Clewett 2015) where annual growth of a pasture sown in 2007 averaged 2730 kg/ha TSDM and another sown in 2012 averaged 4300 kg/ha TSDM. Pastures in Rehab 1, Rehab 2, Rehab 3 and the Control paddock were established in 2007, 2010, 2012 and 2012 respectively, making them of ages similar to the commercial pasture.

Seasonal variation in ADG of cattle during the trial was typical of the region and ranged from weight losses in winter to gains exceeding 1.0 kg/head.day during summer. Mean ADG calculated from simulated annual LWG (including LWG during all rest periods) during the 5-year trial (Clewett *et al*. 2021) were lower and were estimated to be 0.42, 0.51, 0.40 and 0.39 kg/head.day for Rehab 1, Rehab 2, Rehab 3 and Control respectively. These daily gains were at the lower end of the 0.28–0.71 kg/head.day range estimated for 51 herds across brigalow pastures in central Queensland during the 1991–1992 and 1995–1996 financial years (Bortolussi *et al*. 2005).

Simulated estimates of long-term productivity, economic returns and animal carrying capacity (Clewett *et al*. 2021) for Rehab 3 (the rehabilitated pasture most analogous to the land surrounding the mine) were comparable or higher than estimates for the Control paddock and 14 other sites on unmined lands surrounding the mine site, including six sites on commercial beef properties. The long-term estimated LWG of Rehab 2 (116 kg/ha.year) was similar to average gains of 100 kg/ha.year from the Brigalow catchment study (Radford *et al*. 2007). Estimated LWGs from Rehab 3 and the Control (61 and 53 kg/ha.year respectively) were similar to annual gains of 66 kg/ha (106 kg/steer) from continuous grazing of P-fertilised Rhodes grass pasture from 1974 to 1979 at Kogan, ~100 km west of the Acland site (Russell 1985). Economic returns estimated for Rehab 3 and the Control paddocks (155 and 164 AU\$/AE respectively) were ~20% lower than the AU\$196/AE average observed for commercial enterprises across the Darling Downs of Queensland (Holmes *et al*. 2017). Some of this 20% difference would be due to the financial benefits of practices frequently used on the Darling Downs, such as forage cropping and feeding supplements, to offset the effects of grazing poor-quality winter pastures. Differences in accounting for reduced land condition are also likely.

Opportunities for improving the productivity of rehabilitated pastures

Opportunities were identified in the present study to improve the performance of pastures sown on the Acland and similar rehabilitated lands. Legume-based sown pastures, particularly those based on leucaena (*Leucaena leucocephala*), can increase productivity and economic returns (Peck *et al*. 2017; Bowen *et al*. 2018). Importantly, they can also slow the rundown process (Paton and Clewett 2016) and help achieve a higher 'plateau' at equilibrium levels once the rundown process has completed (Peck *et al*. 2011, 2017), by contributing N to the soil, and boosting organic matter and available-N concentrations for associated grasses. Generally, the more productive the legume, the more N it can contribute. In the present study, only in winter and spring of 2016 was there enough rainfall for growth of the winter-active legumes vetch (*Vicia* spp.), hexham scent (*Melilotus indica*) and medics (*Medicago* spp.), sufficient to boost LWGs of stock and, potentially, contribute to subsequent productivity of the remaining pasture grasses. The summer growing season (October to March) at Acland receives 70% of the average annual rainfall, so a legume with mainly summer growth would likely have more lasting effects on building soil N and reducing the impact of rundown (Peck *et al*. 2011; Clewett 2015). Leucaena-based pastures could be very useful. Although sensitive to frost, the undulating landform of the Acland rehabilitated lands reduces the influence of frost, and it is quite possible that the deep-rooting leucaena may be able to exploit water reserves in the underlying argillaceous mine spoil. The legumes caatinga stylo (*Stylosanthes seabrana*), lucernes (*Medicago sativa*) and desmanthus varieties suited to the area also offer potential. Assessment of fertiliser management would be required, especially for legumes, on rehabilitated lands top dressed with soils of a low P status (McIvor 1984).

The spatial diversity in pasture composition and soil fertility found in the present study also highlighted that careful characterisation, placement and fencing of rehabilitation soil according to its properties, just as is recommended for unmined pastures (Hunt *et al*. 2014; Alexander *et al*. 2018), would enable selective grazing behaviour by cattle to be managed in a way that optimises pasture and cattle performance. Further research is required on rehabilitated lands to evaluate a legume-based rotational grazing system that has grazing pressures consistent with long-term carrying capacity to avoid overgrazing and seeks to achieve sustainable levels of pre-cultivation productivity.

Conclusions

During the present trial, grazed pastures sown on rehabilitated, previously mined land were at least as productive as a pasture sown on nearby unmined land at Acland. The rehabilitated pastures also compared favourably with pastures on commercial properties in the region. Pastures established in 2007 and 2010 on rehabilitated land were more productive than were either the rehabilitated or unmined pastures that were established in 2012, probably due to inherently higher fertility of the soil supporting the older pastures. There was some evidence of pasture rundown, a phenomenon that affects all sown pastures, on both rehabilitated and unmined land. Rundown occurred to varying extents across paddocks due to differing pasture ages and levels of initial soil fertility. Cumulative LWG over the trial grazing periods in each of the 5 years of observation were similar in the Control cohort and one or more of the Rehab paddock cohorts. There were no heavy metal contamination concerns with cattle that grazed rehabilitated pasture.

It was concluded that the Acland rehabilitated pastures supported productive and viable cattle production. The research also highlighted a need for further research that evaluates the pasture and livestock productivity of other rehabilitated lands, adds certainty and predictability to the processes of sown pasture rundown, and that demonstrates the ecosystem service benefits of restoring fertility to degraded land.

Conflicts of interest

The authors declare no conflicts of interest.

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