

Sustainability of beef production from brigalow lands after cultivation and mining. 3. Pasture rundown, climate and grazing pressure effects

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Abstract

Context. The Acland Land System overlying the Walloon sandstone coal deposits in southern Queensland is generally marginal for cropping but well suited to grazing, and thus cultivated land is commonly returned to pasture. Rehabilitation of these lands after open-cut coal mining seeks to be safe, stable and self-sustaining to satisfy requirements for ecologically sustainable development.

Aims. The present paper evaluates the sustainability and economic viability of beef production on (a) lands retired from cultivation and then rehabilitated with sown pastures after open-cut coal mining at the New Acland mine site, and (b) similar nearby pasture lands that were not mined but were also retired from cultivation.

Methods. The GRASP grazing systems model was modified and calibrated with short-term (5-year) grazing trial data (soil, pasture and cattle observations), and then used with long-term (60-year) weather data to estimate effects of land type, pasture rundown, climate and grazing pressure on productivity and economic returns. The productivity of three rehabilitated sites and 15 unmined sites were evaluated, including pastures on six commercial properties.

Key results. Estimates of long-term mean annual growth of pastures on unmined lands retired from cultivation on three land types (Mountain Coolibah, Brigalow Uplands and Poplar Box) were 3398, 2817 and 2325 kg/ha respectively. Pasture growth was greater on rehabilitated lands; 3736 kg/ha on the site most typical of rehabilitated lands and a mean of 4959 kg/ha across three sites. Seasonal conditions had large effects on cattle liveweight gain (133–213 kg/head per year during the trial); however, pasture growth was the main driver of beef production and economic returns per hectare. In GRASP, potential nitrogen uptake was used to influence key pasture growth processes and accounted for 64% of variation in observed annual growth. The short-term lift and subsequent rundown in productivity typically associated with sown pastures was estimated to have increased mean annual pasture and cattle productivity during the 2014–2018 trial period by up to 17% and 25% respectively. Estimates of long-term mean annual beef production and economic returns for the unmined lands were less than estimated for rehabilitated lands and were 139 kg/head.year (45 kg/ha.year) and AU\$154/adult equivalent.

Conclusions. Rehabilitated lands were found to be sustainable for beef production at grazing pressures up to 30% utilisation of annual pasture growth, and comparable with grazing systems on native and sown pastures in good condition. Pastures on unmined lands retired from cultivation had reduced productivity.

Implications. Overgrazing is a significant and on-going residual risk to sustainable production. Grazing regimes need to continually adjust for changes in novel landscapes, pasture condition and climate. The methods used in the present study could be applied more generally.

Keywords: cattle, climate, grazing management, pasture production, modelling, sustainable grazing systems.

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Introduction

Sustainable land use is a pivotal concept in agriculture and is defined as an ability to continue through time (Hansen 1996). Thus, a sustainable land use is one resilient to changes in the environment that affect productivity in both the short and long-term. Adjustments in grazing management are needed to accommodate short-term changes in productivity due to factors such as climate variability (Paton *et al.* 2011) and the rundown of sown pastures (Radford *et al.* 2007; Peck *et al.* 2011, 2017). Resilient land management practices are required to overcome threats of overgrazing on pasture condition and productivity and long-term threats of soil erosion, nutrient depletion and climate change (McKeon *et al.* 2004, 2009; McKenzie *et al.* 2017). Sustainability also includes biophysical, economic and social factors operating at field, farm and wider scales (Smith and McDonald 1998), with sustainability being a required attribute in assessing land use suitability for alternative agricultural uses (Queensland Government 2015).

Rehabilitation of land after mining is the process of making a former mine site safe, stable and self-sustaining, and is a requirement of mining best practice and certification of lands as ecologically sustainable (Bell 1996; Queensland Government 2014; Butler and Anderson 2018; McCullough *et al.* 2018). In rehabilitating land for return to commercial agriculture, the aim is to achieve an equal or improved level of land use suitability compared with land use before mining. For example, where grazing lands are used for open-cut coal mining, then successful rehabilitation requires operations to backfill the mine, restore the landform, replace top-soil, re-establish pastures and then adopt on-going management practices that once again provide sustainable grazing, economic returns and social benefits that equal or exceed levels before mining. Practices used for on-going grazing management on progressively rehabilitated lands are centrally important because a key part of the rehabilitation process is in managing the residual risk (Wilson 2018) that arises from the likelihood and impact of future events such as drought and overgrazing.

While poor environmental outcomes have often resulted from inadequate rehabilitation priorities and methods (Mulligan 1996; AusIMM 2018), practices to better manage landform, top soil, erosion, sodicity and vegetation have been developed. This has resulted in many cases of successful rehabilitation using sown pastures (Roe *et al.* 1996; Griffiths and Rose 2017) with characteristics that have some similarities to pastures sown on cropping lands that have been retired to grazing. Pastures sown for mine site rehabilitation and on land retired from cropping are both novel ecosystems and, consequently, a period of transience of several years or more in productivity and potentially species composition is to be expected before ecological stability is achieved (Hobbs *et al.* 2006; Buisson *et al.* 2019).

The present paper is the fourth in a series evaluating results from the Acland Grazing Trial located on rehabilitated lands at the New Acland open-cut coal mine (−27.27, 151.72) in the subtropical central Darling Downs region of southern Queensland, Australia. The trial aimed to assess the

sustainability and viability of cattle production from rehabilitated mined land compared with beef production from nearby unmined pasture lands (Newsome *et al.* 2014) and results have been regularly discussed with the local community and industry (e.g. Clewett *et al.* 2018). Field observations from the trial are described in three papers regarding the soils, pastures, grazing system and beef production (Bennett *et al.* 2021; Paton *et al.* 2021; Melland *et al.* 2021). The grazing trial was established in 2013 by the Acland Pastoral Co. on land that had been previously used for dairy, beef and crop production before open-cut coal mining began in 2002.

The study area forms part of the Acland Land System (Vandersee 1975) of the Brigalow Region and has a mean annual rainfall of 642 mm. Local soils, typically Dermosols and Vertosols (Isbell 2002) are derived from the underlying labile fine-grained sandstone of the Walloon Coal Measures (Wainman and McCabe 2019), or overlying tertiary basalt flows (Vandersee 1975). The soils are suited to grazing but most are marginal for cropping because of susceptibility to erosion, sodic subsoils and shallow depths that limit soil water availability. The soils vary in depth and fertility, causing spatial variability in agricultural production and have been subject to severe erosion, structural decline and nutrient depletion from intensive agriculture (cultivation, dryland grain and/or forage cropping and dairying with high-intensity grazing) (Heijnen *et al.* 1999; Partridge *et al.* 2009; McKenzie *et al.* 2017). This has led to a large proportion of marginal crop lands in the region such as those in the Acland Land System being retired to pasture, with ~76 000 ha being retired in the region (Biggs 2007; Partridge *et al.* 2009). These pastures are typically based on subtropical grasses such as Rhodes grass (*Chloris gayana*), Gatton and green panic (*Megathyrsus maximus* formerly *Panicum maximum*) and creeping blue grass (*Bothriochloa insculpta*), and before rundown are quite productive. However, the productivity of these pastures in comparison to pastures on lands without a history of cultivation has not been quantified.

Vegetation in the area before clearing formed a mosaic of ecosystems (Sattler and Williams 1999) with mountain coolibah (*Eucalyptus orgadophila*), brigalow (*Acacia harpophylla*) and poplar box (*Eucalyptus populnea*) being indicative of geology, soils and productivity, and, hence, these tree species are valuable for defining land types (State of Queensland 2019) for use in land management (Alexander *et al.* 2018). While high grazing pressures can return short-term economic benefits (Bowen and Chudleigh 2018), history shows that a key challenge and risk in managing both native and sown pastures in the region for beef production is to avoid losses in pasture condition and productivity through overgrazing (Tohill and Gillies 1992; McKeon *et al.* 2004; Bortolussi *et al.* 2005b; Maczkowiack *et al.* 2012).

The GRASP grazing systems model (McKeon *et al.* 1990, 2000, 2010; Clewett *et al.* 1998; Rickert *et al.* 2000) adapted for sown pastures (Clewett 2015) is used in the present paper to evaluate and compare the productivity and economic returns of beef production from (a) lands previously used for cultivation and cropping but then rehabilitated with sown pastures after open-cut coal mining, and (b) sown pastures

on similar nearby lands that have also been cultivated and cropped but not used for open-cut coal mining. An overarching aim was to integrate short-term (5-year) field observations from the Acland Grazing Trial with GRASP modelling and simulation studies, to assess the long-term productivity and economic viability of beef production from rehabilitated mined land compared with that from surrounding unmined lands that are used as reference points to benchmark levels of productivity.

Land type, pasture rundown, weather conditions and grazing management usually have strong influences on productivity and economic returns, and are, therefore, considered as four key elements in the analyses of sustainability and economic viability. Pasture rundown is a common feature of sown pastures. They are novel ecosystems and the rundown is characterised, first, by an initial lift in productivity in the first 18 months after establishment that generally exceeds the productivity of ecologically stable pastures, and then, a reduction in productivity over several years as the system returns to stability. Pasture quality, inferred from the pasture nitrogen (N) concentration, usually follows a similar pattern. The cause of this lift and fall in productivity and pasture quality is attributed to short-term changes in the availability of soil N due to soil disturbance and the balance of N mineralisation and immobilisation processes (Graham *et al.* 1985; Robbins *et al.* 1986; Peck *et al.* 2011, 2017). The modelling considers pasture rundown effects together with the effects of long-term cultivation on nutrient depletion and productivity (McKenzie *et al.* 2017). Effects of climate and grazing pressure on pasture condition and losses in productivity from overgrazing are evaluated to assess residual risks to sustainability and to identify grazing management guidelines for sustainable production.

Materials and methods

The GRASP model was used to, first, estimate pasture growth, cattle production and economic returns for the Acland Grazing Trial experimental period (23 Jan 2014 to 22 June 2018) and then, second, to evaluate the sustainability of pastures and beef production via simulation experiments based on long-term (60-year) analyses of the grazing system. Parameters in GRASP were calibrated to the soil, pasture and cattle observations on rehabilitated (rehab) and unmined land of the Acland Grazing Trial. Methods for these observations are fully described in companion papers by Bennett *et al.* (2021), Paton *et al.* (2021) and Melland *et al.* (2021) and are summarised below to provide adequate context for the present paper.

The Acland Grazing Trial had three rehab paddocks (named Rehab 1, Rehab 2 and Rehab 3) and an unmined control paddock (Control) plus a series of benchmark sites surrounding the Acland coal mine on unmined commercially managed grazing lands. Eight of the benchmark sites (named BMK 2, 3, 7, 10, 11, 12, 16 and 18) were assessed for pasture productivity in the final 2 years of the trial and were evaluated using the GRASP model. These lands had been cultivated and cropped for at least five decades

(Carey 2009) before their return in recent years to pasture and grazing, as described below. Further field measurements of pasture productivity on lands previously used for cropping were recorded from a parallel study (Clewett 2015) of pasture growth on six commercial beef properties in the region (named Colliery Park, Mirrabooka, Roundview, Cattle Camp, Oaklands and Oakleigh).

All unmined sites (Control paddock, BMK sites and commercial properties) were grouped by land type (State of Queensland 2019), on the basis of the three main land types of the Acland Land System surrounding the mine (Alexander 2021). This grouping of unmined sites by land type provided a basis for comparison of productivity; particularly for comparisons with rehab lands. The land type and spatial distribution of sites is shown in Fig. 1.

Site descriptions

All sites were cleared of trees except for the Mirrabooka site, which had mature trees (basal area of 3 m²/ha) on steep topography with shallow soil. The Control paddock and BMK sites on gently undulating rises and hills surrounding the Acland mine were located on clay soils (mainly Vertosols and Dermosols) on three land types named after the original vegetation. These land types and some key characteristics (Harris *et al.* 1999; SKM 2008; Alexander 2021) are as follows:

- Mountain Coolibah Open Woodlands (BMK sites 2, 3 and 7) formed on tertiary basalt commonly on low hills and often with high-phosphorus (P) soils but can be very shallow, as in the case of BMK 2 because of the underlying basalt rock
- Brigalow Uplands (Control paddock plus BMK sites 11 and 18) usually on mid- to lower slopes and formed on Walloon sandstones with low to high-P soils and often with saline sodic subsoils
- Poplar Box Uplands (BMK sites 10, 12 and 16) usually on lower slopes and drainage lines with soils derived from the Walloon sandstones that are often low in P with saline sodic subsoils.

This stratification also fitted four of the six commercial properties (Roundview, Cattle Camp, Colliery Park and Mirrabooka), as shown in Fig. 1. The Oakleigh paddock was a Brigalow Plains land type and was added to the Brigalow Uplands group, and the Canimbla paddock on Poplar Box Plains was added to the Poplar Box Uplands group.

Rehab pastures on the Acland mine site were first sown to pasture with a mix of tropical pasture species in 2005 and continued each year as the continuous mining and rehabilitation process progressed to the south-west. Soil and the Walloon sandstone overburden (mine spoil) was removed in strips from the mine's leading edge and then hauled to backfill and rehabilitate the trailing edge of the mine (SKM 2008). The new undulating landform of mine spoil was shaped, contour ripped, top-dressed with the recovered soil layer to a target depth of at least 30 cm and then seeded without fertiliser. The rehab lands used for the Acland Grazing Trial were established by 2007, 2010 and 2012 and were fenced as the following paddocks: Rehab 1 (22 ha), Rehab 2 (32 ha) and Rehab 3 (22 ha) respectively. The unmined Control paddock

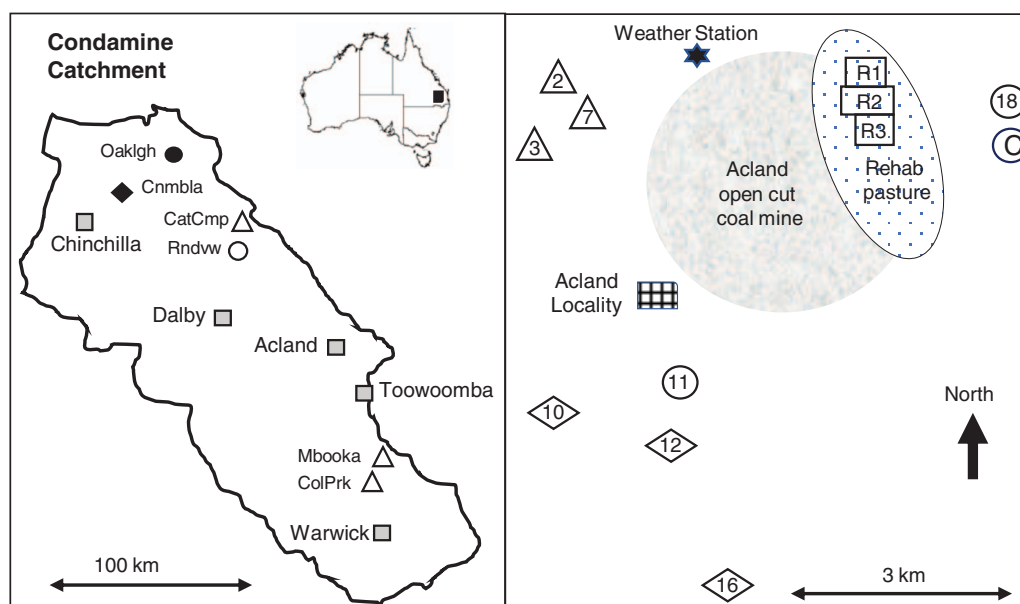


Fig. 1. Locations and land types of the field observation sites across the Condamine River catchment in the Darling Downs region (left panel), and near Acland (right panel) with (1) Acland Grazing Trial pasture and cattle observation paddocks shown as R1 (Rehab 1), R2 (Rehab 2), R3 (Rehab 3) and the unmined Control paddock as (C) on a Brigalow Uplands land type, and (2) the eight unmined benchmark sites at Acland numbered 2, 3, 7, 10, 11, 12, 16 and 18, and the six commercial beef properties shown as Cnmba (Canimbla), CatCamp (Cattle Camp), ColPrk (Colliery Park), Mbooka (Mirrabooka), Oaklgh (Oakleigh) and Rndw (Roundview). Land type symbols are as follows: Mountain Coolibah Open Woodlands on basalt (open triangle), Brigalow Uplands (open circle), Brigalow Plains (solid circle), Poplar Box Uplands (open diamond) and Poplar Box Plains (solid diamond). Squares in left panel show township locations. Star in right panel shows location of the automatic weather station.

(21 ha) was sown to pasture in 2012. This 5-year span in pasture establishment enabled evaluation of differences in pasture rundown patterns.

The Acland mine is located within the mapped boundary of a Brigalow Uplands Land Resource Area (LRA; Harris *et al.* 1999) and combines a range of land types across the mine site, including Brigalow Uplands and Mountain Coolibah (Harris *et al.* 1999; SKM 2008; Carey 2009). It is likely that Vertosol and Dermosol soils were retrieved for the rehab paddocks and were derived from both of these land types, creating differences in soil fertility between sites. Soil analyses of the Vertosol and Dermosol soils of the Acland trial sites (Bennett *et al.* 2021) showed low organic carbon (1.4%) and total N (0.08%) for the Control paddock and BMK sites (0–60 cm profile means), and that these unmined sites were nutrient depleted compared with the nutrient status of virgin soils. Soils in the Rehab 3 paddock were similar. However, the carbon and N concentrations of the Rehab 1 and 2 paddocks were significantly higher. Means for the 0–60 cm soil profile for carbon and total N in Rehab 1 were 1.3% and 0.10% respectively, and in Rehab 2 they were 1.8% and 0.13% respectively. Plant-available P concentrations (Colwell P, 0–60 cm) were variable across the trial sites. They were low in the Control and Rehab 3 paddocks (5.0 and 11.6 mg/kg respectively) but high in Rehab 1 and 2 paddocks (29.1 and 35.4 mg/kg respectively).

Most unmined sites were retired from cultivation to pasture in the period of 2003–2012, as shown in Table 1. Rhodes grass

(*Chloris gayana*) and creeping blue grass (*Bothriochloa insculpta*) were the most frequently encountered species across sites (Clewett 2015; Melland *et al.* 2021; Paton *et al.* 2021). Some notable variations in species composition and condition included the following: Gatton and green panic (*Megathyrsus maximus*) in the Rehab 1 and 2 paddocks, Gatton panic at Colliery Park, high proportions of Queensland blue grass (*Dichanthium sericeum*) in BMK sites 3 and 16, buffel grass (*Cenchrus ciliaris*) in the pastures at Oakleigh and Canimbla, couch grass (*Cynodon dactylon*) exceeding 95% of the pasture at Roundview, and winter active legumes such as medics (*Medicago* spp.), lucerne (*Medicago sativa*) and vetches (*Vicia sativa*) present in several paddocks in some years. The Rehab paddocks and all unmined sites were in good (A) pasture condition, except five sites that had been in pasture for at least 10 years; the BMK 2 site was in B condition, BMK 10, Roundview and Mirrabooka sites were in poor (C) condition, and the BMK 11 site was in very poor (D) condition (Table 1). Indicators of potential pasture productivity at each site (soil water storage and potential N uptake as described further below) are also shown in Table 1.

The rehab and control paddocks of the Acland Grazing Trial were maintained in pasture condition A over the 5 years of the trial by applying best management practices (Paton *et al.* 2011). The paddocks were periodically grazed at stocking rates of 47–171 adult equivalents (AE) per 100 ha (Melland *et al.* 2021) where an AE represents a 450 kg *Bos taurus* steer growing ~150 kg/year. There were 17 grazing periods with

Table 1. Field site characteristics concerning (a) pasture condition, location and year of pasture establishment, (b) estimated maximum soil water storage (field capacity minus lower limit) in soil layers L1 (0–10 cm), L2 (10–50 cm), and L3 (below 50 cm) and (c) estimated values of potential annual nitrogen (N) uptake (kg/ha) by pastures

Values of potential N uptake are indicative of soil fertility. Initial values were derived by calibrating the GRASP model to the Swiftsynd field observations, and final values were adopted for the grazing simulation studies after minor recalibration to the Botanal field observations of TSDM. All pastures were in A condition, except where (B), (C) and (D) suffixes indicate B, C and D pasture condition. Lower boundary of L3 was set to 80 cm for most sites, 60 cm for BMK 2, BMK 10 and Mirrabooka sites, 70 cm for BMK 11, BMK 16, Colliery Park, Roundview and Cattle Camp sites, and 120 cm for Rehab sites

| Land type | Site and pasture condition | Location (latitude, longitude) | Year sown | Maximum soil water storage (mm) | | | Potential N uptake (kg/ha.year) | |
|-------------------|----------------------------|--------------------------------|-----------|---------------------------------|----|----|---------------------------------|-------------|
| | | | | L1 | L2 | L3 | Initial value | Final value |
| Rehab | Rehab 1 | -27.271, 151.720 | 2007 | 23 | 83 | 62 | 26.7 | 24.1 |
| | Rehab 2 | -27.275, 151.715 | 2010 | 23 | 83 | 62 | 35.6 | 33.1 |
| | Rehab 3 | -27.278, 151.724 | 2012 | 23 | 83 | 62 | 17.6 | 19.5 |
| Brigalow Uplands | Control 1 | -27.286, 151.746 | 2012 | 21 | 83 | 49 | 18.4 | 16.9 |
| | Control 2 | -27.284, 151.743 | 2012 | 19 | 84 | 49 | 15.0 | |
| Mountain Coolibah | BMK 18 | -27.277, 151.745 | 2009 | 22 | 83 | 47 | 19.8 | 19.8 |
| | BMK 11 (D) | -27.317, 151.695 | 2003 | 20 | 83 | 32 | 11.2 | 11.2 |
| | Roundview (C) | -26.876, 151.451 | 1979 | 20 | 83 | 32 | 13.0 | 13.0 |
| | Oakleigh | -26.549, 151.111 | 2003 | 21 | 83 | 49 | | 16.7 |
| | BMK 2 (B) | -27.273, 151.667 | 2004 | 21 | 43 | 23 | 16.2 | 16.2 |
| | BMK 3 | -27.287, 151.651 | 2007 | 23 | 83 | 49 | 21.3 | 21.3 |
| | BMK 7 | -27.276, 151.680 | 2009 | 23 | 81 | 48 | 13.9 | 13.9 |
| Poplar Box | Colliery Park 1 | -27.975, 151.923 | 2008 | 21 | 83 | 32 | 19.8 | 19.8 |
| | Colliery Park 2 | -27.976, 151.933 | 2013 | 21 | 83 | 32 | 19.7 | 19.7 |
| | Cattle Camp | -26.787, 151.469 | 2007 | 21 | 83 | 32 | | 21.0 |
| | Mirrabooka | -27.835, 152.059 | | 21 | 31 | 8 | | 23.5 |
| | BMK 10 (C) | -27.362, 151.705 | 2003 | 23 | 83 | 17 | 8.0 | 8.0 |
| Poplar Box | BMK 12 | -27.329, 151.686 | 2007 | 24 | 83 | 49 | 14.9 | 14.9 |
| | BMK 16 | -27.362, 151.705 | 2006 | 24 | 83 | 32 | 11.9 | 11.9 |
| | Canimbla | -26.673, 150.748 | 2007 | 19 | 83 | 56 | | 17.1 |

either three or four grazings each year of 6 (± 2) weeks, followed by a rest period of 8 (± 4) weeks. Cattle were either grazed in 'rest' paddocks when not grazing the trial paddocks or were sold with a new cohort (usually young steers) purchased in spring for the next year of grazing. The cohort purchased in spring 2015 was retained in spring 2016 and grazed the trial paddocks for 2 years. Livestock numbers were adjusted for each period of grazing and set in accordance with pasture production to maintain an equivalent grazing pressure across all paddocks. Grazing management aimed to achieve 30% utilisation of annual pasture growth, a level considered to be ecologically sustainable, commercially relevant and equal to the 'safe' utilisation rate used in defining long-term carrying capacity, as discussed below.

Field observations

Soil core samples were collected to 1 m depth in the Acland Grazing Trial sites twice per year for 5 years. Five soil cores along five transects in each of the rehab and control paddocks, and three cores within 10 m of a fixed location at each of the benchmark sites were collected and bulked at 10–20 cm depth intervals. Physical characteristics of the soil core samples (including soil texture and bulk density) were measured once during the trial and chemical attributes of the samples (including soil pH, carbon, N, P and sodicity) were measured once or twice per year. Root distribution was measured at the end of the trial by using soil pits (Bennett *et al.* 2021). The

above physical and chemical soil characteristics were also measured on commercial properties (Clewett 2015).

Pasture observations of total standing dry matter (TSDM) were made within ungrazed fenced exclosures (12 m \times 12 m) by using the Swiftsynd methodology (Day and Philp 1997) for (a) 3 years (2013–2015) at the Colliery Park and Roundview sites, (b) 5 years (2014–2018) at sites within the rehab and control paddocks and (c) 2 years (2017–2018) on the eight benchmark sites (Paton *et al.* 2021). The exclosures were mown to ground level in September–October, at the start of the growing season in spring each year. TSDM (separated to grass and dicots) was measured from four quadrats (0.5 \times 0.5 m) of the exclosure in early summer, mid-summer and at the end of the growing season in mid-autumn. The TSDM data and analyses of pasture N content at each harvest were used to calculate pasture growth rates and to calibrate parameters in the GRASP model.

Estimates of TSDM under grazing were also made three or four times per year across each of the Acland Grazing Trial paddocks (Melland *et al.* 2021) and across each of the grazed paddocks on the commercial property sites. These observations were made using the Botanal methodology (Tothill *et al.* 1992) of visually estimating TSDM, cover and percentage green and recording species present in ~50 quadrats per paddock, with quadrats regularly spaced along four transects across the paddock. Botanal observations were made immediately before each period of grazing of the Acland

Grazing Trial, with the observations being used to guide subsequent stocking rates. Cattle liveweights were recorded at the start and end of each grazing period. On the commercial properties, the Botanal observations were made at the end of the growing season (mid-autumn). Grazing management on all properties varied with seasons and all employed periods of pasture spelling. Methods used to calculate statistically significant differences in pasture and cattle observations are given by Paton *et al.* (2021) and Melland *et al.* (2021).

GRASP description

The GRASP (Grass Production) model (McKeon *et al.* 1990, 2000, 2010; Rickert *et al.* 2000) has been routinely used for analysis of grazing systems (e.g. McKeon *et al.* 2000; Scanlan *et al.* 2011, 2014; Clewett 2015; Peck *et al.* 2017). It was developed as a robust weather-driven, daily time-step model for simulating the growth and condition of grazed and ungrazed native pastures in northern Australia through time periods of several seasons to >100 years.

Weather inputs to GRASP are daily historical values of rainfall, minimum and maximum temperature, vapour pressure, solar radiation and synthetic pan evaporation. This enables simulation of the daily soil water balance and estimates of water losses via runoff, deep drainage, soil evaporation and plant transpiration. The main driver of pasture growth in GRASP is transpiration. Growth is also modified by the effects of N availability, light interception, temperature, potential growth rate, pasture condition and tree competition. Estimates of pasture quality (%N), senescence and detachment rates enable daily estimates of pasture growth, TSDM and N uptake. Annual beef production (per head and per hectare) is estimated as a function of length of growing season, annual pasture utilisation (quantity of pasture eaten by livestock as a percentage of pasture growth) and stocking rate. Daily changes in animal liveweight have consequent effects on intake of pasture and provide feedback effects of grazing pressure on pasture growth. There is also a feedback of pasture utilisation on pasture condition that operates on an annual basis and this enables simulation experiments to assess the influence of grazing pressure on pastures, beef production and sustainability.

Gridded daily weather data (January 1889 to June 2018) from the SILO database (Jeffrey *et al.* 2001) on the LongPaddock website (Stone *et al.* 2019) were used for input to GRASP simulations for the Acland Grazing Trial sites and for sites on commercial properties. A location near the Acland township (-27.30, 151.70) was used for the grazing trial paddocks and benchmark sites. This was supplemented by rainfall and temperature data from an automatic weather station located on the mine site (-27.267, 151.698) for the 2014–2018 trial period, with several gaps being in-filled with SILO data. The Acland Grazing Trial and benchmark sites were within 7 km of the mine site weather station. The Rainman software (Clewett *et al.* 2003) was used for climate analyses.

Parameters defining plant-available water in GRASP were estimated from (1) field measurements of soil texture, bulk density and root distribution (Bennett *et al.* 2021),

(2) estimates of field capacity as a function of soil texture (% clay) using the data and equations of Rab *et al.* (2011), and (3) parameters in the GRASP model derived from field data (Day *et al.* 1997a; McKeon *et al.* 2010) to define the lower limit of soil water in each layer as a function of field capacity. Soil water was estimated for two upper-soil layers of fixed depth (0–10 cm and 10–50 cm) and a third layer below 50 cm of variable depth to a maximum of 120 cm. The depth of soil covering the mine spoil in the rehab paddocks was variable (45 ± 30 cm) and these paddocks were modelled as two layers of soil and the third layer as mine spoil with the texture of light clay containing 40% rock fragments. The mine spoil should be a potentially useful contributor to soil water storage and plant growth because it is a labile argillaceous material of medium to very fine-grained sandstone derived from volcanic fragments with a high proportion of pore space filled by smectite clays (Wainman and McCabe 2019). It was explored by plant roots, is moderately alkaline (pH 8.3), has a high cation exchange capacity and the salinity, sodicity and toxicity levels were of no concern (Bennett *et al.* 2021). Basalt rocks at depth and near the surface of the BMK 2 and Mirrabooka sites were modelled to reduce water storage by 30% in the lower layers.

Adaptation of GRASP to assess beef production from sown pastures

The sown pastures version of GRASP (Clewett 2015) used in the present study has added modules for pasture establishment, pasture rundown, N uptake, growth of legumes, changes in soil carbon and economic returns. This version of GRASP (referenced as G21-sc3b) is based on the GVT89 series of GRASP FORTRAN used for WinGRASP (Clewett *et al.* 1998; Rickert *et al.* 2000) and analyses of native pasture grazing systems of McKeon *et al.* (2000) and Scanlan *et al.* (2010, 2014). The pasture establishment module requires parameters specifying dates and costs for land preparation and seeding, levels of rainfall to trigger germination and establishment and limitations on grazing. The module for growth of legumes is for perennials and, thus, was not applicable to the episodic self-regenerating annual legumes encountered in the study. The soil carbon module is based on the ROTHC model (Coleman and Jenkinson 1999) that estimates changes in soil carbon as a function of soil type, temperature, soil moisture and pasture biomass.

Pasture rundown module

Pasture rundown was modelled as a rapid rise in potential pasture productivity in the year following pasture establishment, followed by a slower rundown in productivity over several years. The cause of this initial lift and subsequent slow-down in productivity was attributed to changes in N uptake from two processes. First, a rapid increase in N availability and uptake associated with soil disturbance from land rehabilitation processes (earth moving and pasture planting) causing a rapid breakdown of soil organic matter and mineralisation of N, and, second, a subsequent reduction in N availability and uptake over several years due to the immobilisation of N into soil organic matter (Graham *et al.*

1985; Robbins *et al.* 1986; Peck *et al.* 2011, 2017; Thornton and Shrestha 2021).

Three parameters were used to estimate rundown, including (1) the level of potential N uptake per year (parameter p99 denoted as p99) equal to the value of p99 at the start of simulation, (2) an initial lift in potential N uptake in the first year (p543) following land disturbance, and (3) a third parameter (p544) governing the rate of pasture rundown defined as the length of time (years) required to reduce the extra N availability to 5% of the initial lift via exponential decay as in Thornton and Shrestha (2021). These two latter parameters were defined through calibration as functions of p99, with p543 as $0.7 \times p99$, and p544 as $0.3 \times p99 - 1.0$, with minimum and maximum values of 2 and 11 years. Thus, in fertile soils such as in the Rehab 1 and Rehab 2 paddocks (Bennett *et al.* 2021), pasture rundown was modelled to occur with a larger initial lift and to then decline over a longer period than in less fertile soils such as in the Rehab 3 and Control paddocks (Fig. 2a). Values of p544 derived from the final calibrated values of p99 for the grazed Rehab 1, 2 and 3 and Control paddocks (Table 1) were 6.2, 8.9, 4.9 and 4.1 years respectively.

Nitrogen uptake module

Several components in GRASP for estimating pasture growth were modified to capture annual changes in soil fertility associated with pasture rundown and also the key role of N in regulating plant growth. The following text describes how five parameters that are normally held as constants through time during simulation were changed at the start of each year.

The potential annual N uptake parameter (p99, kg/ha) was changed to become a variable to reflect changes in the availability of soil N. It is defined as the maximum level of N uptake (calculated from %N and TSDM) that can occur during the growing season in those years when growth is limited by N availability and not by weather conditions. The value of p99 was maintained at its starting value in simulations until the year after the sown pasture planting date, and was

then calculated at the start of each year from the following exponential decay equation:

$$p99 = p99Y1 + p543 \times \min(1.0, \exp(-3.0/p544 \times (t - 1)))$$

where p99Y1 is the starting value of p99, and t is the number of years after sowing.

Nitrogen availability has large effects on the rate of plant growth processes (Sinclair and Horie 1989; Sadras *et al.* 2016). Calibrated parameter values reported by Day *et al.* (1997a) and McKeon *et al.* (2010) for a range of land types show that land types with higher levels of potential N uptake also tend to have higher values for potential regrowth rate of pasture (p6), growth rate per unit of plant transpiration (p7) and radiation use efficiency (p8). Therefore, p6, p7 and p8 were also changed to become variables and were increased between limits as a function of p99, as follows:

$$p6 = \max(2.0, \min(10.0, 0.150 \times p99))$$

(kg/ha per day per unit of basal area)

$$p7 = \max(8.0, \min(25.0, 0.625 \times p99))$$

(kg/ha.mm of transpiration)

$$p8 = \max(6.0, \min(24.0, 0.4 \times p99 + 4.0))$$

(kg/ha per MJ/m² of solar radiation)

Similarly, the rate of N uptake (p98) following an initial uptake of 5 kg/ha of N was estimated as a function of potential N uptake in two stages. First, a linear stage in proportion to the rate of transpiration that continued until 70% of N uptake had occurred (defined by cumulative transpiration equal to p680, where the accumulation is from the N reset date at the start of the growing season). A second curvilinear stage logarithmically reduced the rate of N uptake to near zero as N uptake approached p99 (Fig. 2b). It was defined by a second parameter (p681) that specified the cumulative transpiration when 97% of potential N uptake had occurred.

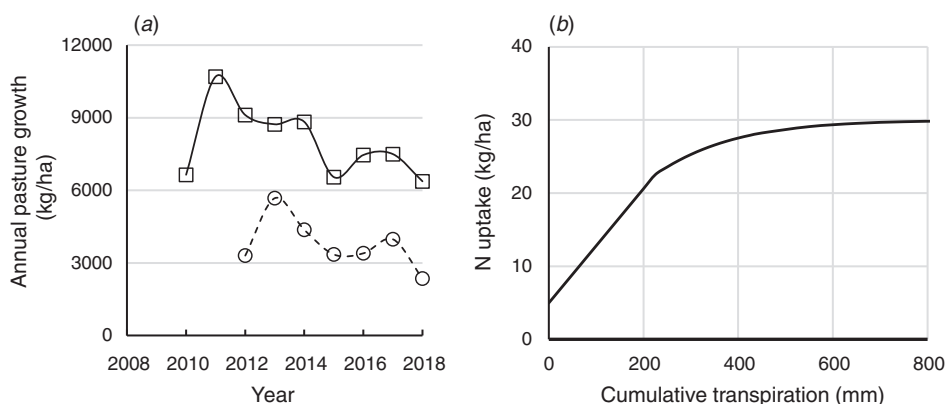


Fig. 2. (a) Estimated annual growth of pasture from GRASP simulations of Rehab 2 (squares) and Control (circles) paddocks from establishment (2010 in Rehab 2 and 2012 in Control), showing the initial lift in productivity followed by a pasture rundown phase over several years interacting with climate variability, and (b) N uptake as a function of cumulative transpiration since the start of the growing season with a potential N uptake of 30 kg/ha.

The parameter specifying the minimum level of N concentration in green leaves (p101) was not changed and was held as a constant through time.

Economics module

The economics module was set up to calculate operating gross margins for a steer growing operation. This included cattle costs per head for purchase, transport, health and sale, but excluded capital costs for land, labour and pasture establishment. An interest cost on cattle purchased (5% per annum) was applied to enable estimates of stocking rate effects on economic returns. Cattle costs were based on purchase of young steers landed on farm on 1 July, which then grow 130–230 kg over 12 months to produce feeder steers (e.g. 410–510 kg at 22 months) for sale to feedlot on 30 June. Cattle sale prices were based on mean values (2014–2018) of the Eastern Young Cattle Indicator price and the Dalby saleyard price margin for young steers (3% higher than the Eastern Young Cattle Indicator). After adding transport costs, this gave a purchase price of AU\$2.73/kg liveweight for young cattle landed on farm. Sale price (AU\$/kg) of feeder steers (400–500 kg) were generally lower than that of young cattle and averaged 86% of yearling price (AU\$/kg) over the trial period. Costs for animal health (AU\$7/head), marketing (5.5% of sale price) and mortality (0.5%) were applied.

Model calibration

The objective function used in model calibration was the minimum root mean square of differences (RMSD) between observed values and model estimates. Some observed values rated as outliers (possibly caused by experimental factors such as rainfall variability) were excluded from the calibration process but were included in comparative statistics such as linear regression of predicted versus observed. Microsoft Excel (2016) was used for the regression analyses, and, except where stated, the linear regressions of estimated versus observed were forced through the origin.

All parameters were initialised to the standard native pasture parameter set. Pasture growth parameters were first calibrated using the Swiftsynd data from the ungrazed exclosures and were then carried forward to the second stage of calibration where pasture senescence and detachment parameters were calibrated to Botanal estimates of TSDM under grazing.

Cattle production parameters were calibrated to the observed liveweight gain data recorded on entry and exit from the 17 grazing periods of the trial, with cattle numbers in the model being the same as those applied in the field. During the rest periods of the trial, the continuity of animal liveweight and liveweight gain estimates for the trial paddocks were maintained in GRASP by reducing stocking rates to 1% of the 'trial' rate and, thus, (a) modelled pastures could recover from grazing under this very light grazing regime, and (b) modelled estimates of annual liveweight gain (1 July to 30 June) could be calculated. Animal liveweight was initially set to the first observed value of a cattle cohort and this value was excluded from calculations of RMSD, means and

linear regression statistics of slope and coefficient of determination (R^2).

The 'warm-up' period for GRASP is generally 3 years; however, this was extended to the first 10 years of simulation when calculating long-term means, so that effects of pasture rundown were removed. Weather conditions in 2016–2017 were conducive to the growth of legumes (Melland *et al.* 2021), contributing greatly to annual cattle liveweight gain. Legume growth was estimated to add 25 kg/head to liveweight in the Rehab 1, Rehab 3 and the Control paddock and 28 kg/head in Rehab 2. This gain is consistent with Peck *et al.* (2017) and was modelled by increasing the potential seasonal liveweight gain for that year. This enabled better agreement of simulated liveweight gain with the observed data across all years of the trial. However, the episodic and phosphate-dependent growth of annual legumes and their potential to supply N to pastures and protein to cattle (Clarkson 1989; Clarkson *et al.* 1987; Peck *et al.* 2011) were not included in the following simulation experiments.

Simulation experiments

The calibrated model was used in simulation experiments to evaluate the grazing system by estimating changes in pasture growth, rainfall use efficiency, stocking rate and livestock carrying capacity, pasture utilisation (percentage of annual pasture growth eaten by cattle), cattle liveweight gains and gross margins. These outputs are collectively referred to as key performance indicators. Liveweight gain parameters derived for the Acland Grazing Trial rehab and control paddocks were applied to the benchmark and commercial property sites. The same economic parameters were applied across all sites. Nil grazing pressure from other herbivores was assumed. The simulation experiments assessed the following:

- (1) Effects of pasture rundown on productivity. Simulations that gave a mean annual grazing pressure of 30% utilisation of annual pasture growth were run with and without the effects of pasture rundown.
- (2) Effects of land type on long-term (60-year) mean annual key performance indicators calculated for the Mountain Coolibah, Brigalow Uplands and Poplar Box land types, in comparison with results for the rehab paddocks. The analysis used a 10-year model warm-up period (1 July 1948 to 30 June 1958), with sown pasture established in Year 1, so that pasture rundown was completed by the end of the warm-up period. The following 60-year simulation period from 1 July 1958 to 30 June 2018 aimed to achieve a long-term mean annual utilisation of 30% of annual pasture growth. Trial and error adjustment of stocking rates based on estimated TSDM present at the end of the growing season (1 May) was used for each site in a series of simulation runs until the target of 30% utilisation was achieved.
- (3) Effects of climate variability on probability distributions of the key performance indicators. This simulation examined changes in the key performance indicators for each 5-year period over the 120-year period from 1 July 1898 to 30 June 2018. A 10-year warm-up period preceded each 5-year period. These data were used to

assess the presence of increasing or decreasing trends in pasture growth. Effects of climate change and the relationship of the average Southern Oscillation Index (SOI) during winter and spring with the key performance indicators were examined.

- (4) Effects of grazing pressure on the key performance indicators. Stocking rates were adjusted in this simulation experiment with the intake of young cattle on 1 July each year to consume 1%, 10%, 20%, 30%, 40% and 50% of TSDM at the end of the growing season (1 May) over the following 12 months. These 60-year simulations examined the effects of adjusting grazing pressure to levels that diverge from the estimated 'safe' level of 30% utilisation, and also made the following assumption. Parameter settings in GRASP that governed pasture growth and condition responses to grazing pressure were based on the findings from neighbouring regions and are further addressed in the following section, and in the discussion of results.

Persistently high grazing pressure is specified in GRASP to cause a loss of pasture condition, which then reduces soil water availability, N uptake and pasture growth. Changes in pasture condition are estimated as a function of annual pasture utilisation using continuous ramp relationships (Clewett 2009) fitted to the stepped functions quantified from the studies of Ash *et al.* (1996, 2002) and McKeon *et al.* (2000). This approach enables grazing management studies to avoid unstable outcomes where pasture condition and utilisation rates are near the thresholds of stepped processes (Scanlan *et al.* 2014; Clewett 2015). The pasture condition state in GRASP with a range of 0 (pasture in good condition) to 11 (pasture in very poor condition) is (a) either reduced or improved if annual pasture utilisation is respectively higher or lower than 35% as in McKeon *et al.* (2000), and then (b) is transformed to percentage perennial grasses in the pasture (Fig. 3). The maximum change in any year is one pasture condition unit if the annual utilisation of pasture growth is <20% or >50%. If pastures are subjected to continuous heavy grazing (exceeding 50% utilisation each year) for 3, 5, and 7 years, then pastures are reduced from 90% perennials

(pasture in A condition) to 70%, 34% and 11% perennials respectively. This is equivalent to pastures in B, C and D levels of pasture condition respectively, with productivity being reduced to less than 75%, 45% and 25% of pastures in A condition (Quirk and McIvor 2007; Alexander *et al.* 2018). Long-term carrying capacity reports from FORAGE (Zhang and Carter 2018) also use these values for B and C condition and a value of 20% for D condition. Recovery in pasture condition (through light grazing) is enabled if pasture is in B or C condition, but is prevented if pasture is in D condition.

Results and discussion

The following sections first describe weather conditions during the trial period, and the calibration results of estimated values from GRASP simulations compared with the observed values for TSDM and pasture quality (%N) from the Swiftsynd exclosures, TSDM values derived from Botanal observations, and cattle liveweights. Results and discussion of the simulation experiments follow, concerning pasture rundown, effects of land type, and climate and grazing management, before concluding with a general discussion.

Weather conditions during the trial period

Weather conditions during the 5-year trial period (January 2014 – June 2018) at Acland were variable. Mean annual rainfall (July–June) for the trial period (562 mm) was 13% less than the long-term (1898–2018) mean of 642 mm, with some periods being very dry such as the 2014–2015 and 2017–2018 seasons when rainfall was 26% below the long-term mean in both of these years (Fig. 4). Rainfall was summer dominant (38% of average annual rainfall) and least frequent in winter (16% of average annual rainfall). Pasture growth was strongly seasonal, with growth mainly following spring and summer rainfall events (Fig. 5). Winter pastures for grazing were generally characterised by limited pasture growth and 20 frosts/year causing low-quality forage and low to negative cattle liveweight gain. Winter and spring rainfall during 2016 promoted the growth of winter active legumes and this was then supplemented by autumn rainfall in 2017 that kept pastures green and was estimated to infiltrate to the lower

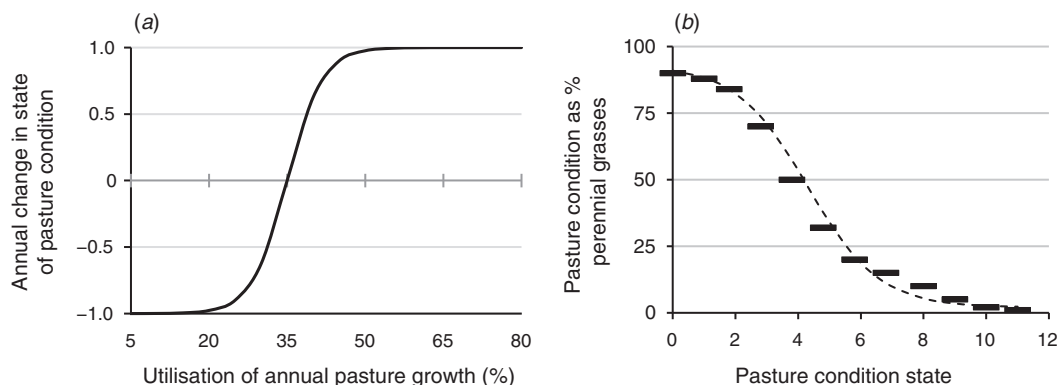


Fig. 3. GRASP functions for estimating changes in pasture condition. (a) Influence of percentage utilisation of annual pasture growth on annual changes in pasture condition state, and (b) transformation relationship (dashed line) derived to estimate pasture condition (expressed as percentage perennial grasses in the pasture) from the stepped pasture condition states (horizontal bars) quantified by the studies of Ash *et al.* (1996) and McKeon *et al.* (2000).

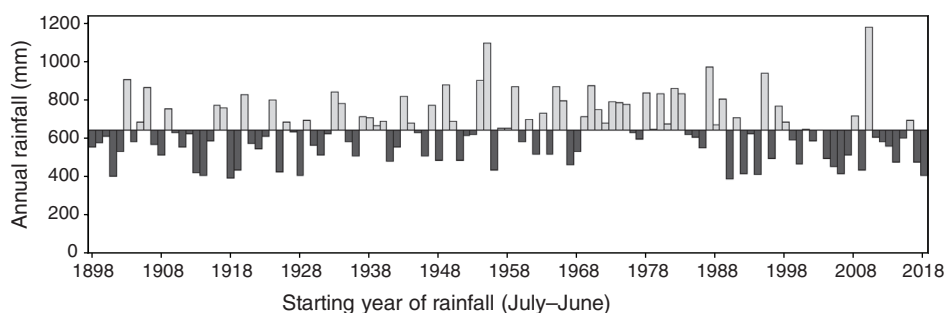


Fig. 4. Departure of annual rainfall (July to June) from mean annual rainfall (642 mm) for the 121-year period 1 July 1898 to 30 June 2019 at Acland, with the starting year shown on the x-axis.

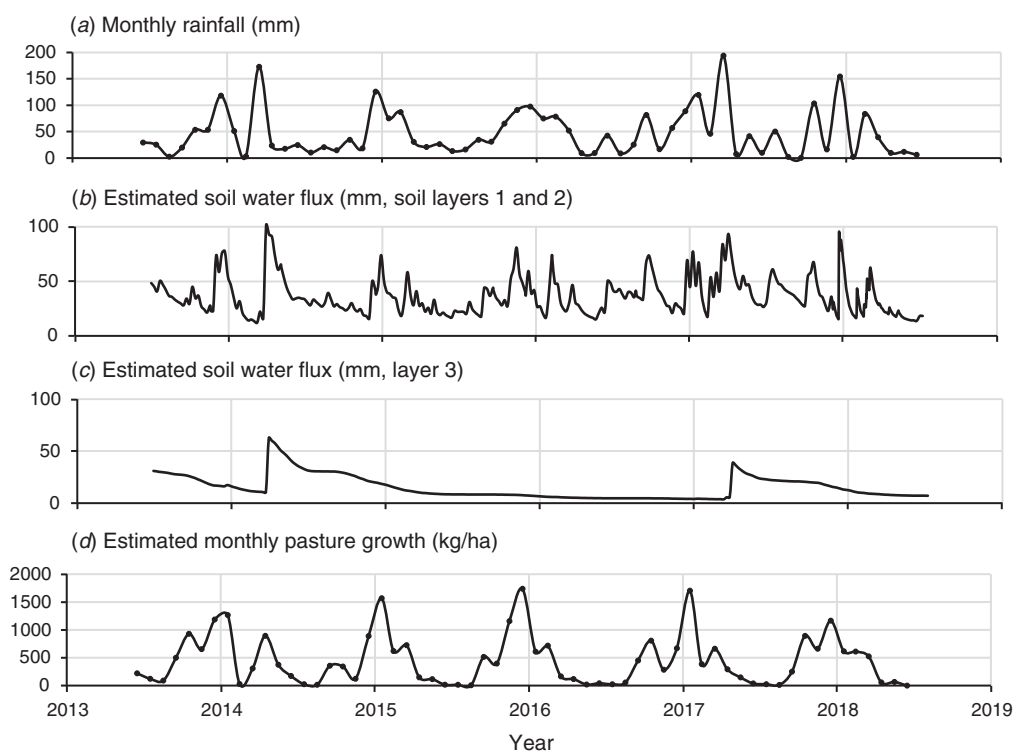


Fig. 5. Changes during the trial period (July 2013 to June 2018) in rainfall and GRASP estimates of soil water and pasture growth: (a) monthly rainfall, (b) estimated daily soil water flux in the upper soil profile (0–50 cm), (c) estimated daily soil water flux in the lower profile (50–120 cm layer of mine spoil) of the Rehab 1 Swifts synd enclosure, and (d) estimates of monthly pasture growth in the Rehab 1 Swifts synd enclosure.

soil layer (Fig. 5). Consequently, the 2016–2017 season had an extended period of above-average rainfall and provided good conditions for grazing and cattle liveweight gains. Rainfall during the 3-year observation period on the commercial properties (2013–2015) was near average in the first year, 21–34% below average in Year 2 and marginally below average (nil to 16%) in Year 3. Mean annual rainfall at these locations generally reduces from east to west and was as follows: Mirrabooka (735 mm), Colliery Park (683 mm), Roundview (658 mm), Cattle Camp (720 mm), Oakleigh (643 mm) and Canimbla (618 mm).

Calibration of GRASP to Swifts synd pasture observations

Simulations with the calibrated GRASP model gave estimates of pasture TSDM that were similar to the observed values in the Swifts synd enclosures and to the Botanal observations across the grazed paddocks.

Observed and estimated pasture TSDM across all Swifts synd sites had means of 2902 and 2809 kg/ha respectively ($n = 114$, RMSD = 832 kg/ha, $cv = 29\%$). Regression analyses of GRASP estimates versus observed values gave R^2 values of 0.78 ($n = 114$, slope = 0.912) across all sites (Fig. 6a), 0.80 ($n = 103$, slope = 0.931) for

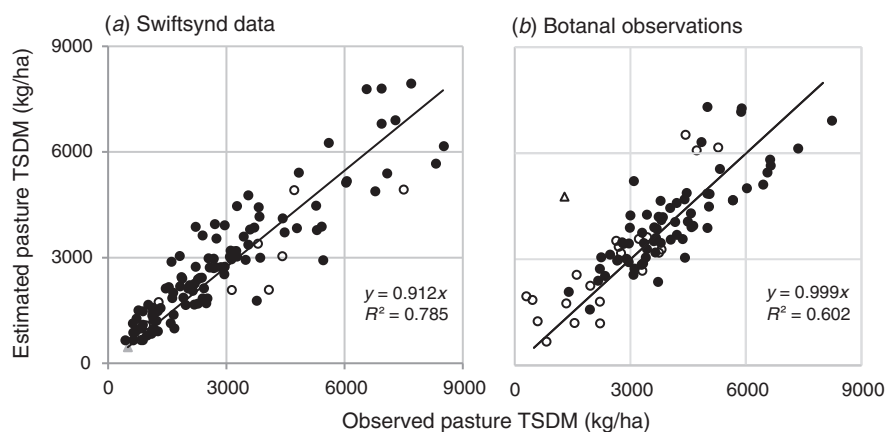


Fig. 6. GRASP estimates versus field observations of pasture TSDM for (a) Swiftsynd exclosures in the rehab and control paddocks, eight unmined BMK sites surrounding Acland mine and three exclosures on two commercial properties, and (b) Botanal observations of grazed pasture TSDM from the rehab and control paddocks and six commercial properties. Acland Grazing Trial and BMK site observations are shown as solid points and commercial properties as open circles. The outlier observation (triangle) was not included in calibration, but is included in the regression statistics.

the Swiftsynd exclosures at Acland (rehab and all unmined lands), and 0.74 ($n = 11$, slope = 0.757) for the Swiftsynd sites on commercial properties. Observed values of TSDM in Swiftsynd exclosures on rehab sites were much greater than those on unmined land. In rehab exclosures, the mean TSDM over all harvests for observed and estimated were similar (3962 and 3960 kg/ha respectively, with RMSD = 945 kg/ha), and significantly ($P < 0.05$) greater than the observed and estimated TSDMs over all harvests for unmined land (2351 and 2211 kg/ha respectively, RMSD = 767 kg/ha).

Land type was associated with large differences in observed values of TSDM. The weighted means of observed TSDM at the end of the growing season in mid-autumn for Poplar Box, Brigalow Uplands and Mountain Coolibah land types were 2233, 3393 and 4006 kg/ha (Paton *et al.* 2021). The corresponding mean autumn TSDM for the rehab sites was 5644 kg/ha and this varied from 3716 kg/ha for Rehab 3 to 7400 kg/ha for Rehab 2. The time series diagram of observed and predicted TSDM values over the 5 years of the Acland trial in Paton *et al.* (2021) illustrates the large differences in productivity that were observed among sites.

In calibrating GRASP parameters to achieve best estimates of TSDM, the central focus of calibration was to adjust values of p99 to minimise RMSD for TSDM rather than adjusting p99 to observed values of N uptake. This approach was taken because the key drivers of pasture growth (potential regrowth rate, transpiration efficiency, radiation efficiency and the rate of N uptake) were modelled as functions of p99 as described in the methods, and consequently, the value of p99 represented more than could be derived from observed values of N uptake. Final values of p99 for each Swiftsynd site (Table 1) led to estimates of potential N uptake that accounted for 64% of variation ($n = 48$) in observed pasture TSDM at the end of the growing season in the Swiftsynd exclosures (Fig. 7a).

The % N content of TSDM and its dilution to minimum levels at the end of the growing season has a strong influence

on GRASP estimates of TSDM. Observed values of % N at the end of the growing season in the grass component of pastures tended to be lower in mid-autumn than in early summer, as expected, across the Acland trial and BMK sites and ranged from $0.60 \pm 0.20\%$ N in the first 3 years of the trial to $0.42 \pm 0.15\%$ N in the last 2 years. This reduction in pasture quality with an increasing pasture age was also reflected in the rundown of N uptake (Paton *et al.* 2021); however, the influences of pasture rundown on minimum values of % N were not developed into the model and the normal practice of specifying a constant value for minimum % N (parameter p101) in GRASP was retained. A constant value for p101 equal to the observed mean %N of TSDM in mid-autumn across all Swiftsynd exclosures over the 5-year trial at Acland of 0.46% N was assumed for all sites. This resulted in a weak relationship ($R^2 = 0.57$, slope = 0.487, $n = 103$) of predicted versus observed N uptake (Fig. 7b). Errors were greatest in the first few years after pasture establishment when % N and N uptake levels were high. Improvements to the N module in GRASP would be useful.

Calibration of GRASP to Botanal pasture observations

Values of soil and pasture growth parameters identified in the calibration of GRASP for the Swiftsynd exclosures were also used for the grazed paddocks, except for some small changes in the value of potential N uptake (p99). The value of p99 was marginally reduced for Rehab 1 and Rehab 2 and marginally increased for Rehab 3 (Table 1) on the basis of calibration to the observed Botanal pasture TSDM data. These minor changes were expected and were possibly due to spatial differences between the small Swiftsynd exclosures and the larger grazed paddocks.

Botanal pasture observations across the Acland Grazing Trial paddocks (from 14 January 2014 to 18 April 2018) showed the Control paddock to have a significantly ($P <$

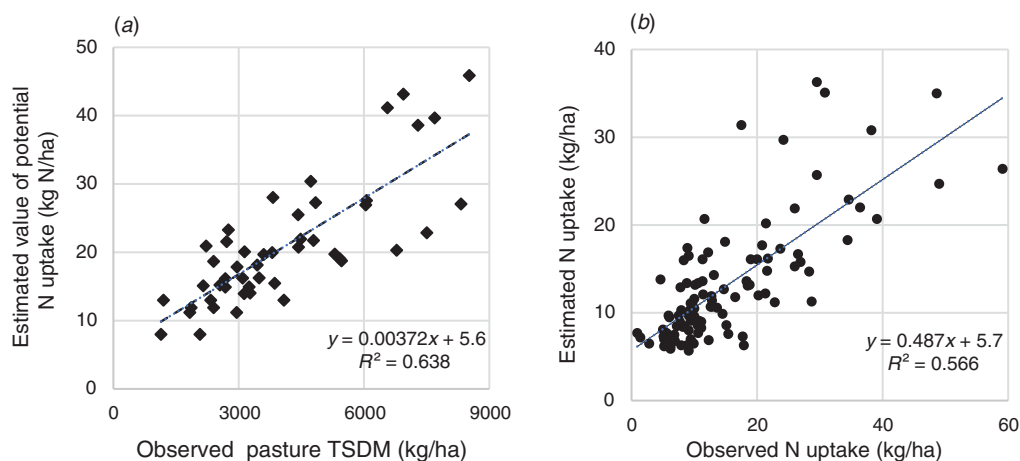


Fig. 7. (a) Estimated value of potential N uptake (p99) versus observed TSDM in Swiftsynd enclosures in autumn, and (b) GRASP estimates of N uptake versus observed values from Swiftsynd enclosures at Acland.

Table 2. Observed and GRASP estimates of mean TSDM from Botanal observations, AE days grazing and cattle liveweight for the 17 periods of grazing during the 5-year trial (147 days/year on average)

Modelled estimates of liveweight were reset each year to the first entry and, thus, this value was discarded from the comparison.

| Site | TSDM (kg/ha) | | AE days grazing/year | | Liveweight (kg/head) | |
|---------|--------------|--------------|----------------------|-------|----------------------|--------------|
| | Observed | GRASP (RMSD) | Observed | GRASP | Observed | GRASP (RMSD) |
| Rehab 1 | 3965 | 3992 (615) | 37.6 | 37.3 | 386 | 383 (16.7) |
| Rehab 2 | 5656 | 5644 (1253) | 47.2 | 48.6 | 403 | 406 (18.1) |
| Rehab 3 | 3609 | 3601 (615) | 37.2 | 37.2 | 385 | 383 (18.5) |
| Control | 2871 | 3086 (948) | 37.2 | 37.2 | 390 | 388 (19.9) |
| Mean | 3962 | 3960 (832) | 38.7 | 39.0 | 391 | 390 (18.3) |

0.05) lower mean TSDM (2871 kg/ha) than did the other sites (Melland *et al.* 2021). Rehab 2 had a significantly ($P < 0.05$) higher mean TSDM (5656 kg/ha) than did other sites and the Rehab 1 and Rehab 3 means were similar. Despite these differences, the pastures were morphologically similar, and, therefore, the same set of grazing parameters in GRASP was used for all paddocks of the grazing trial. This resulted in optimum values of summer and winter detachment of 0.0039 and 0.0024 kg/kg.day respectively. These values were applied to both leaf and stem. Similarly, the effect of trampling on pasture TSDM was calibrated to the same value (30%) for all paddocks.

GRASP simulations using the same periodic grazing pattern as used in the grazing trial gave estimates of TSDM very similar to the observed Botanal estimates, as shown by the means in Table 2. RMSD values of differences between observed and estimated TSDM were similar to the standard deviations of observed TSDM. The regression slope of estimated TSDM versus observed across all sites was close to unity (slope = 0.999, $n = 89$, $R^2 = 0.60$; Fig. 6b). Regression statistics were $R^2 = 0.47$ ($n = 51$, slope = 0.977) for the rehab paddocks and $R^2 = 0.73$ ($n = 21$, slope = 1.126) for paddocks on commercial properties. The Control paddock contained an outlier (reasons unknown), as shown in Fig. 6b. When the outlier is included, the $R^2 = 0.13$, and when it is excluded, the

Control paddock regression statistics are $R^2 = 0.48$ ($n = 16$, slope = 0.979).

The values of R^2 on grazed paddocks were lower than in the Swiftsynd enclosures, partly because of greater site variability with large paddocks and partly because of increased complexity under grazing conditions (due to senescence, detachment and grazing impacts), and partly because TSDM was maintained at fairly constant levels (Fig. 8). This occurred as a result of continual stocking rate adjustments associated with the periodic grazing and feed budgeting regime of the grazing trial to achieve a constant grazing pressure of ~30% utilisation of annual pasture growth. Actual levels of mean annual pasture utilisation during the trial were estimated by GRASP simulations to be 25.8%, 27.5%, 28.2% and 31.1% for the Rehab 1, 2 and 3 and Control paddocks respectively.

Calibration of GRASP to cattle liveweight observations

The average duration of grazing the trial paddocks was 147 days per year (40% of days) and this varied from 117 days in Year 5 to 190 days in Year 4. GRASP simulation of pasture and animal production over the trial period using the same periodic grazing regime and livestock numbers gave estimates of AE days grazing very similar to

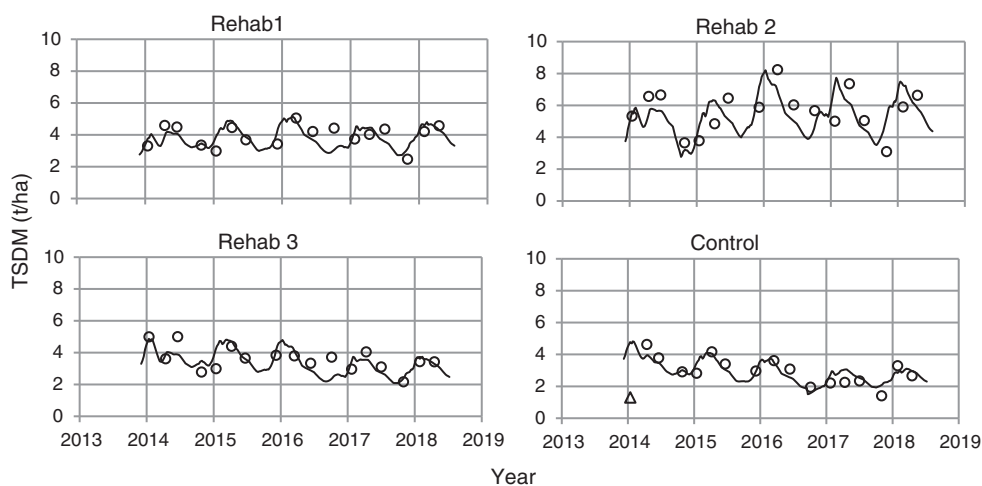


Fig. 8. Changes in pasture TSDM over the 2014–2018 trial period for the Rehab 1, 2 and 3 paddocks and the unmined Control paddock. GRASP estimates are shown as solid lines and the mean value of Botanal observations as circles. The outlier observation (triangle) was not included in calibration.

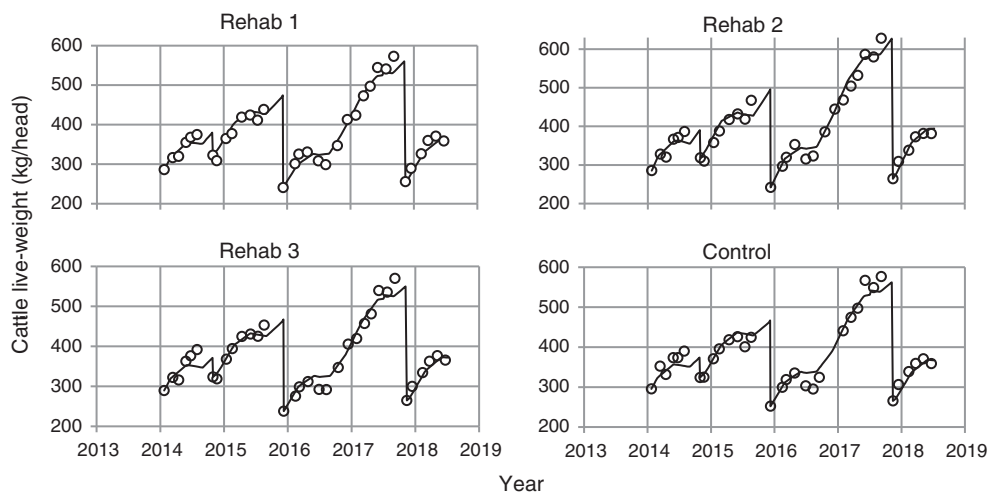


Fig. 9. Changes in animal liveweight over the trial period while grazing the Rehab 1, 2 and 3 paddocks and the unmined Control paddock. GRASP estimates are shown as solid lines and observed values as circles.

those calculated from the observed entry and exit weights at each grazing (Table 2; $R^2 = 0.99$, slope = 1.01, $n = 67$).

GRASP estimates of cattle liveweight gains for the Acland Grazing Trial were in close agreement with observed values (Fig. 9). The mean observed and estimated cattle liveweights were 391 and 390 kg respectively (RMSD = 18.3 kg/head, 4.7% of the mean). The regression slope for all paddocks was close to unity (0.995) with $R^2 = 0.95$ ($n = 115$) and exceeding 0.92 in each paddock. Estimated mean annual liveweight gain (kg/head from 1 July to 30 June) for the 5 years of the trial was 157 kg/head (0.43 kg/head.day), which is typical of brigalow pastures, but 26 kg/head below the average of commercial herds with access to supplements and growth promotants that graze brigalow pastures in central Queensland (Bortolussi *et al.* 2005a). Mean annual liveweight gain per head varied among paddocks and was 143 in the Control paddock, 153 and 146 in Rehab 1 and 3 paddocks respectively and 187 in the

Rehab 2 paddock, and reflected differences in observed liveweight gains during the measurement periods of the grazing trial. Gains in Rehab 2 were similar to or significantly greater ($P < 0.05$) than in the other three paddocks (Melland *et al.* 2021) and, thus, Rehab 2 was calibrated to have a marginally higher rate of annual liveweight gain. The coefficient for calculating changes in annual liveweight gain due to changes in length of growing season (percentage of growth index days above 0.30) was calibrated to 0.0065 for the Control, Rehab 1 and Rehab 3 paddocks, and to 0.0076 for Rehab 2. The annual liveweight gain model derived for the Control paddock was applied to all BMK sites and all paddocks on commercial properties.

The influence of pasture rundown on diet quality and liveweight gain was not clear. Pasture N uptake (kg/ha of N) was found to decrease exponentially with pasture age in Rehab 2, Rehab 3 and one of the Control Swiftsind sites

(Paton *et al.* 2021) but not in Rehab 1, which was sown 7 years before the start of the trial and may have already reached a stable level of productivity. Rundown in pasture quality (leaf protein) was also found to occur with increasing pasture age in all four trial paddocks (Melland *et al.* 2021); however, faecal analyses showed that increases in pasture age were not associated with a statistically significant ($P < 0.05$) decrease in the diet quality (%N) selected by cattle. Therefore, the parameters in GRASP influencing this aspect of liveweight gain were set to have no effect.

Weather conditions had large impacts on pastures and liveweight gain, with estimated mean liveweight gains across all paddocks for each year of the trial varying from 134 kg/head in Years 2 and 3, to 142 kg/head in Year 5, and 169 and 208 kg/head in Years 1 and 4 respectively.

The estimated mean utilisation of annual pasture growth across all paddocks was 28% and varied between 17% and 41%. Rehab 1 had the lowest mean grazing pressure of 26%, Rehab 2 and 3 were similar to the overall mean of 28%, and the Control paddock was higher at 31%. Comparison of productivity from each of the paddocks under the same grazing pressure (30% utilisation of pasture growth) led to small changes in estimates of pasture growth, stocking rates and livestock production during the trial (Table 3). While a mean of 30% annual utilisation was achieved, the simulated variation was 26–38% during the trial period. Tactical variation in stocking rates based on TSDM values at the end of the growing season has several shortcomings (Hunt 2008) and can lead to considerable variation in utilisation of pasture growth (e.g. when years of high TSDM are followed by droughts, or *vice versa*). Variation in annual utilisation rates during the 60-year simulation were greatest in the Control (11–65%) and lowest in Rehab 2 (16–46%).

Effects of pasture rundown on productivity and economic returns

The effects of pasture rundown on productivity were assessed by comparing (a) the productivity of the grazing system during the trial period when pasture rundown was actively occurring with (b) estimates of productivity from the same years but from a long-term 60-year simulation in which the parameters specifying the initial lift and subsequent rundown of sown pasture growth were set to negligible levels. The grazing

pressure applied in both simulations was adjusted during the trial period to give a mean annual pasture utilisation of 30%, estimated as the long-term sustainable 'safe' utilisation rate.

Estimated mean annual pasture growth for all paddocks during the trial (4991 kg/ha) was 12% higher than the estimate (4451 kg/ha) for the same period during the long-term simulation. The effects were strong in recently established pastures (17% and 14% respectively for Rehab 3 and Control) sown in 2012 and least (1%) in the oldest pasture (Rehab 1, sown in 2007; Table 3). Rehab 3 was estimated to have increased annual N uptake levels by 6.7, 2.2 and 0.2 kg/ha in Years 1, 3 and 5 respectively, of the trial, giving rise to increases in annual pasture growth of 1443, 476 and 43 kg/ha respectively. The Control paddock gave similar increases and a rapid loss in productivity. In contrast, the estimated increases in N uptake and longevity of rundown were higher in Rehab 2, probably because of its observed higher soil fertility levels concerning soil organic carbon, N and P (Bennett *et al.* 2021). Following establishment in 2010, the estimated lift in annual N uptake and pasture growth of Rehab 2 during 2011–2012 was 17 and 3705 kg/ha respectively. In the subsequent trial years, the annual N uptake level in Rehab 2 steadily decreased and was reduced to 9.3, 4.4, and 2.2 kg/ha in Years 1, 3 and 5 of the trial respectively. The estimated lift in pasture growth during these years was 2035, 967 and 497 kg/ha respectively and equivalent to lifts in productivity of 34%, 15% and 8% respectively.

Consequential effects of increased pasture growth during the trial years led to estimates of increased animal productivity and economic returns, with the largest effects being on gross margins (Table 3). Observed pasture rundown effects on pasture quality during the trial period (Melland *et al.* 2021; Paton *et al.* 2021) and its likely effects on liveweight gain (Partridge *et al.* 2009; Peck *et al.* 2011) were not included in the model.

Effects of land type on productivity and economic returns

Long-term (60-year) simulation of the grazing system across 19 sites gave mean annual production levels of 3375 kg/ha of pasture growth, a stocking rate of 32 head/100 ha, 143 kg/head liveweight gain and economic returns of AU\$51/ha, equating to AU\$154/AE. The estimated mean daily intake across all

Table 3. Estimates of mean annual productivity and economic returns during the 5-year trial period (2013–2018) concerning pasture growth, stocking rate, cattle liveweight gain and gross margin

The elevated levels of productivity and economic returns estimated to have occurred during the trial period due to the initial post-sowing lift in pasture production that is followed by rundown are shown in parentheses as a percentage of the mean. Data are based on a mean annual grazing pressure of 30% utilisation during the trial period

| Paddock | Pasture growth (kg/ha.year) | Stocking rate (AE/100 ha.year) | Liveweight gain (kg/ha.year) | Gross margin (AU\$/ha.year) |
|---------|--------------------------------|-----------------------------------|---------------------------------|--------------------------------|
| Rehab 1 | 4572 (1) | 43 (2) | 77 (4) | 77 (5) |
| Rehab 2 | 7503 (16) | 64 (10) | 134 (15) | 171 (20) |
| Rehab 3 | 4320 (17) | 40 (18) | 71 (25) | 69 (44) |
| Control | 3567 (14) | 34 (17) | 58 (18) | 54 (20) |
| Mean | 4991 (12) | 45 (10) | 85 (14) | 93 (22) |

sites was 8.6 kg/AE.day and ranged from 8.4 to 9.0 kg/AE.day. Pasture growth was the main driver of estimated cattle production and accounted for 96% of the variation among sites in estimated liveweight gain per hectare and 71% of the variation in gross margins. In contrast, variation among years was mostly due to variation in liveweight gain per head, as discussed below. The above results are comparable across sites because the simulated stocking rate applied at each site was at an equivalent level of grazing pressure. This was at an estimated long-term sustainable level of 30% utilisation of mean annual (60-year) pasture growth. Estimated stocking rates were based on the level of TSDM present on 1 May and, thus, stocking rate in any year was closely related to pasture growth in the previous year.

Rehab lands were estimated to provide the highest levels of production. Mean annual pasture production of the rehab paddocks (4959 kg/ha) was 77% higher than the mean of the unmined sites (2847 kg/ha; Table 4). This result was strongly influenced by the high productivity of Rehab 2 in comparison to all others and also poor pasture condition of some unmined sites. The Mountain Coolibah land type was the most productive of the unmined sites (3398 kg/ha), followed by the Brigalow Uplands (2817 kg/ha) and the Poplar Box land types (2325 kg/ha). These differences align with observed soil fertility levels (Bennett *et al.* 2021) and carried through to estimates of long-term sustainable stocking rates, beef

production and economic returns (Table 4). While the light clay texture of the argillaceous mine spoil in the lower layer of the rehab paddocks was probably a positive contributor to pasture growth, as evidenced by exploration of roots within this layer (Bennett *et al.* 2021), it is also likely that pasture growth in the Control paddock and at several BMK sites was reduced by structural decline and saline sodic subsoils.

The estimated mean gross margins per head in the rehab paddocks ranged from AU\$155 to AU\$231/AE and were, thus, comparable with estimated mean values for the Darling Downs region (AU\$196/AE; Holmes *et al.* (2017). Gross margins per head on unmined land were generally below the mean for the Darling Downs region.

Effects of climate on productivity and economic returns

Climate variability was estimated to cause large year to year variations in productivity across all sites. For example, drought conditions such as those in 2006–2007 (Fig. 4) reduced mean annual rainfall by 37% and estimates of pasture growth by 55%, beef production by 51% and economic returns by up to 114% to negative values. In contrast, high-rainfall years produced relatively smaller changes in production because of estimated soil fertility restrictions to pasture growth due to limited plant-available N. Differences in mean annual production among simulations over the past 60 years and

Table 4. Estimates of long-term (60-year) mean annual productivity of rehab lands compared with the productivity of unmined land types in the district (as in Fig. 1)

Estimates are from GRASP simulations of pasture growth, rainfall use efficiency (RUE), stocking rates of adult equivalents (AE), beef production and economic returns at a grazing pressure of 30% utilisation of pasture growth. The mean of all unmined land types and the overall mean give equal weight to each land type

| Land type | Site | Pasture condition | Pasture growth (kg/ha) | RUE (kg/ha.mm) | TSDM 30 June (kg/ha) | Stocking rate (AE/100 ha) | Liveweight gain (kg/head) | Gross margin (AU\$/ha) | Gross margin (AUS/AE) | |
|--------------------------------|---------------|-------------------|------------------------|----------------|----------------------|---------------------------|---------------------------|------------------------|-----------------------|-----|
| Rehab | Rehab 1 | A | 4611 | 7.2 | 3350 | 43 | 148 | 76 | 73 | 169 |
| | Rehab 2 | A | 6528 | 10.3 | 4340 | 59 | 169 | 116 | 137 | 231 |
| | Rehab 3 | A | 3736 | 5.9 | 2646 | 36 | 143 | 61 | 55 | 155 |
| | Mean | | 4959 | 7.8 | 3445 | 46 | 153 | 85 | 88 | 185 |
| Mtn | BMK 2 | B | 2977 | 4.7 | 1794 | 28 | 130 | 44 | 33 | 117 |
| Coolibah | BMK 3 | A | 4091 | 6.4 | 2788 | 39 | 140 | 66 | 57 | 146 |
| | BMK 7 | A | 2659 | 4.2 | 1814 | 25 | 136 | 42 | 34 | 136 |
| | Colliery Park | A | 3856 | 5.7 | 2668 | 37 | 146 | 64 | 58 | 144 |
| | Mirrabooka | C | 2740 | 4.8 | 1383 | 26 | 103 | 33 | 11 | 46 |
| | Cattle Camp | A | 4068 | 6.3 | 2751 | 39 | 142 | 66 | 58 | 150 |
| | Mean | | 3398 | 5.3 | 2200 | 32 | 133 | 53 | 42 | 123 |
| Brigalow | Control | A | 3169 | 5.0 | 2363 | 31 | 146 | 53 | 50 | 164 |
| Uplands | BMK 11 | D | 1831 | 2.9 | 1284 | 18 | 144 | 30 | 28 | 160 |
| | BMK 18 | A | 3775 | 5.9 | 2645 | 36 | 141 | 61 | 54 | 151 |
| | Roundview | C | 2309 | 3.7 | 1458 | 22 | 142 | 38 | 33 | 151 |
| | Oakleigh | A | 3002 | 4.9 | 2261 | 29 | 144 | 50 | 46 | 160 |
| | Mean | | 2817 | 4.5 | 2002 | 27 | 143 | 46 | 42 | 157 |
| Poplar Box | BMK 16 | A | 2150 | 3.4 | 1529 | 21 | 140 | 35 | 30 | 147 |
| | BMK 12 | A | 2740 | 4.3 | 2132 | 27 | 150 | 47 | 47 | 177 |
| | BMK 10 | C | 1272 | 1.9 | 948 | 12 | 149 | 22 | 21 | 175 |
| | Canimbla | A | 3136 | 5.3 | 2031 | 29 | 127 | 46 | 33 | 112 |
| | Mean | | 2325 | 3.7 | 1660 | 22 | 142 | 37 | 33 | 152 |
| Mean of all unmined land types | | 2847 | 4.5 | 1954 | 27 | 139 | 45 | 39 | 144 | |
| Overall mean | | 3375 | 5.3 | 121 | 32 | 143 | 55 | 51 | 154 | |

120 years were negligible; pasture growth was 0.2% higher (8 kg/ha) and liveweight gain 1% higher (0.6 kg/ha) over the past 60 years. Regression analysis of time series data over the 120-year period (1898–2018) formed as 24 sets of 5-year means showed no trend in pasture growth (slope = 0.4 kg/ha per year, $R^2 = 0.005$), mainly because of the high frequency of drought years at both the start and end of the 120-year period (Fig. 4). However, the most recent 60-year period (1958–2018) also showed a significant upward trend in mean temperature (0.22°C per decade) and vapour pressure deficit (0.58 hPa per decade), and a significant ($P < 0.05$, $R^2 = 0.46$) downward trend in estimated annual pasture growth of 70 kg/ha per decade. This is consistent with climate change projections that are likely to cause reduced long-term carrying capacity (McKeon *et al.* 2009; Stokes and Howden 2010; Whish *et al.* 2014) and will, therefore, require ongoing advances and communication of best management practices (Paton *et al.* 2011; George *et al.* 2019) for managing climate risk.

Variations in mean annual production and economic returns were also high when estimated from 5 years of data sampled as 24 sequences of 5 years in the period July 1898 to June 2018 (120 years) (Fig. 10). These data derived at an average grazing pressure of 30% utilisation highlighted several issues. First, and in regard to the estimated productivity of the rehab paddocks, Rehab 2 performance was very high and an outlier compared with the 18 other sites, Rehab 1 performed better than all sites other than Rehab 2, and Rehab 3 performance was equivalent to several unmined sites and above that of most unmined sites. Second, the movement in 5-year means was substantial (although much less than annual variation) and deviations from the median were persistent over long periods as illustrated by the annual

rainfall pattern in Fig. 4. Five-year means for pasture growth, liveweight gain and gross margin during the 2013–2018 trial period were similar to, although marginally less than the medians of the 5-year means during the 120-year period from 1898 to 2018. The median value of the 5-year mean for pasture growth when averaged across all sites was 3466 kg/ha and, during the trial, it was 3394 (percentile rank = 0.26). While the liveweight gain and gross margin medians were 142 kg/head and AU\$48/ha, the 5-year means during the trial years were 137 kg/head and AU\$45/ha respectively (percentile rankings of 0.30 and 0.34 respectively). It was concluded that the Acland Grazing Trial was conducted during a period of marginally reduced productivity and economic returns, but was quite typical of the climate and production risk environment.

A third finding evident in the data of Fig. 10 was that differences among sites were much greater than were effects of climate on the 5-year means of estimated pasture growth and, consequently, on stocking rates and liveweight gains/ha. In contrast, differences in liveweight gain per head between sites were small relative to the impacts of climate variability on liveweight gains per head. Effects of climate variability on liveweight gain per head were larger than they were on pasture growth.

Variation in the amount and timing of rainfall caused large variations in liveweight gain between years, ranging from 74 kg/head in drought years to 192 kg/head (mean of 146) in the Control paddock, from 102 to 224 kg/head (mean of 169) in Rehab 2, and from 56 to 176 kg/head (mean of 130) for the shallow soil BMK 2 site with limited soil water holding capacity. Variability of liveweight gain caused by seasonal weather conditions is typical of pastures in the Brigalow

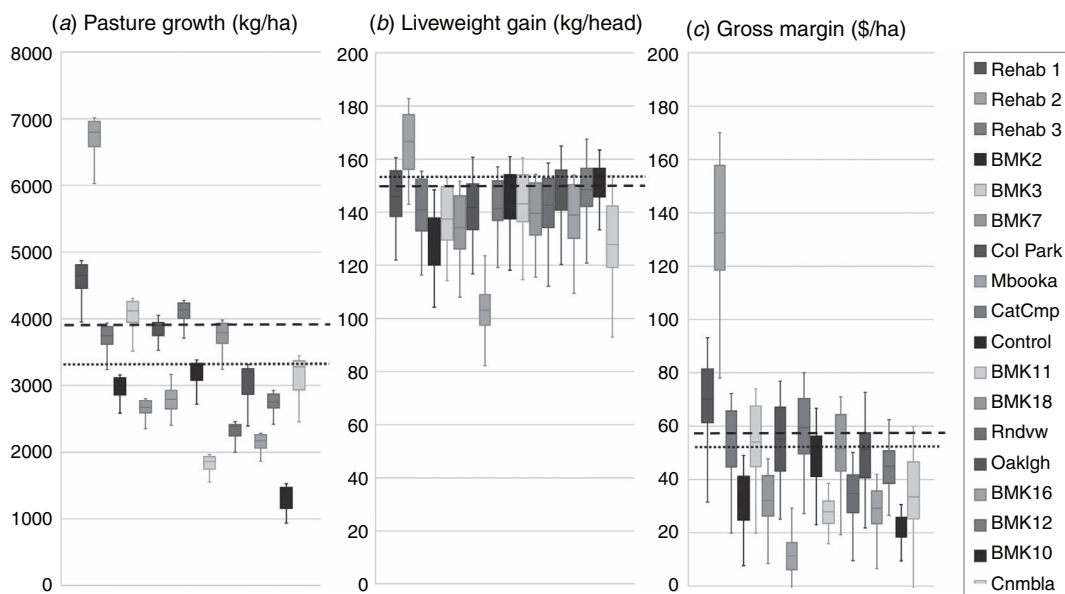


Fig. 10. Frequency distribution of 5-year means of annual productivity and economic returns estimated from 24 sets of five sequential years of data sampled from July 1898 to June 2018 for (a) pasture growth, (b) liveweight gain per head and (c) gross margin. Box plots show minimum, maximum and quartiles, and are arranged in the same order from left to right as legend shows top down. Dashed and dotted lines are the 5-year means for Rehab 3 and Control paddocks respectively, for the observation period of the Acland Grazing Trial (July 2013 to June 2018).

Region (Bortolussi *et al.* 2005a; Radford *et al.* 2007; Burrows *et al.* 2010) and was observed during the trial as large changes in liveweight gain during the year (from -0.26 to 1.62 kg/head/day; Melland *et al.* 2021). Variability is further amplified where pasture quality is also affected by the episodic occurrence of winter-active legumes such as medics (Clarkson 1989). Gross margins had the greatest variation in proportion to the mean. The coefficients of variation (standard deviation of 5-year mean as a percentage of the 5-year mean) for estimated pasture growth, liveweight gain/head and gross margin/ha were 6%, 8% and 26% respectively.

The El Niño Southern Oscillation (ENSO) was found to have a large influence on pasture productivity in spring and early summer. When the monthly average of the SOI for the June to November period was either below -5 or above $+5$, then estimated pasture growth was decreased by 22% or increased by 36% respectively, in the spring–early summer period. However, as expected, the influence on the longer period of annual pasture production was low ($<7\%$) and, thus, changes in annual stocking rates of 10% and 20% in accordance with the SOI (decrease when SOI is negative, increase when positive) had little to no effect on beef production and economic returns. This was in part due to climate factors, but was mainly due to (a) pasture growth under high rainfall conditions being constrained by limited availability of soil N, and (b) the resilience of the grazing system to withstand occasional high levels of utilisation during drought years. Thus, ENSO information is likely to be most useful to short-term tactical management choices relevant to spring and early summer, such as input to short-term feed budgeting for rotational grazing decisions, or variation in methods for establishing pastures. These findings are consistent with conclusions by McKeon *et al.* (2000), Clewett and Clarkson (2007) and O'Reagain *et al.* (2018).

Effects of grazing pressure on pasture condition and sustainability

Simulated changes in grazing pressure from 1% to 50% utilisation of TSDM at the end of the growing season (1 May) were estimated to have large effects on key performance indicators for production and economic returns when tested in long-term (60-year) simulations of the Rehab 3, BMK 3 (Mountain Coolibah), Control (Brigalow Uplands) and Canimbla (Poplar Box) paddocks. Grazing pressures of 1%, 10%, 20% and 30% utilisation of TSDM at the end of the growing season translated in the following year to long-term means across the four land types of 1.4%, 12.4%, 21.8% and 28.9% utilisation of pasture growth with all pastures ending the 60-year simulation in A condition. However, higher grazing pressures (40% and 50% utilisation of TSDM) increased the long-term mean annual utilisation of pasture growth to 35% and 41.1% respectively, had large impacts over time on pasture condition and led to pastures degrading to C and D condition with 25% and 2% perennials respectively, after 60 years of simulation. Returns of liveweight gain/ha and gross margin/ha were maximised at 50% utilisation in the initial years of simulation but fell rapidly over time as pasture condition deteriorated under high grazing pressure. Grazing

trials testing the effects of high grazing pressure have also observed similar responses of early gains and subsequent reductions in productivity and economic returns (O'Reagain *et al.* 2018).

As grazing pressure was increased from 1% to 30% utilisation of TSDM, there was little effect on estimated mean annual pasture growth and pasture condition and almost proportional increases in stocking rate, AE days grazing, beef production and economic returns with equivalent reductions in pasture TSDM. However, as grazing pressure increased to 40% and 50% utilisation, there were rapid reductions in pasture condition that led to reductions in mean annual pasture growth, TSDM, soil organic matter, stocking rates, liveweight gain and economic returns (Fig. 11). Liveweight gain/head and gross margin/AE were different because they first decreased then increased at high levels of utilisation. This upturn is consistent with higher pasture quality and liveweight gain observations on pastures in poor condition (Ash and McIvor 1995; O'Reagain *et al.* 2018) where sufficient forage is available to not limit intake. The upturn in economic returns per head plus high initial rates of economic returns per hectare are likely contributing causes to the use of high (but not sustainable) utilisation rates by industry (Bowen and Chudleigh 2018).

The grazing pressure simulation results in Fig. 11 illustrate the relationships between the production performance indicators, and highlight the residual risk of persistent overgrazing leading to a degraded pasture condition and reduced productivity. However, there is some uncertainty. The influence of grazing pressure on productivity was not observed in the present study. Therefore, the authors cannot be certain of the points of inflection shown in Fig. 11 and the overall response of the grazing system (Ash and Smith 1996). While this uncertainty is also part of the residual risk, it is mitigated by the modelling approach with GRASP that enables the use of data from other studies.

The safe utilisation rate of 30% used in the present study when estimating effects of pasture rundown, land type and climate variability on productivity and economic returns is consistent with best management practice guidelines. This includes utilisation rates specified in data supporting the Stocktake package (Aisthorpe *et al.* 2004; Bath 2016) developed for use in the Darling Downs region by primary producers and agri-business. While safe utilisation rates of 22% and 27% were derived for native pastures in south-eastern Queensland (Day *et al.* 1997a; Hall *et al.* 1998) and the central Burnett (Day *et al.* 1997b) respectively, utilisation rates of 30% are also recommended for native and sown pastures across a range of land types in the neighbouring Moreton and Burnett regions (Partridge 1993; State of Queensland 2019), for Brigalow land types in the Maranoa region (Paton *et al.* 2011) and native spear grass pastures in southern and central Queensland (Hunt 2008; Burrows *et al.* 2010).

The safe utilisation rate of 30% is marginally less than the points of inflection for pasture condition and pasture growth in Fig. 11. Therefore, the 5% buffer between the safe utilisation level and the inflection point at 35% in the pasture condition response curve in Fig. 3 was appropriate in the present study

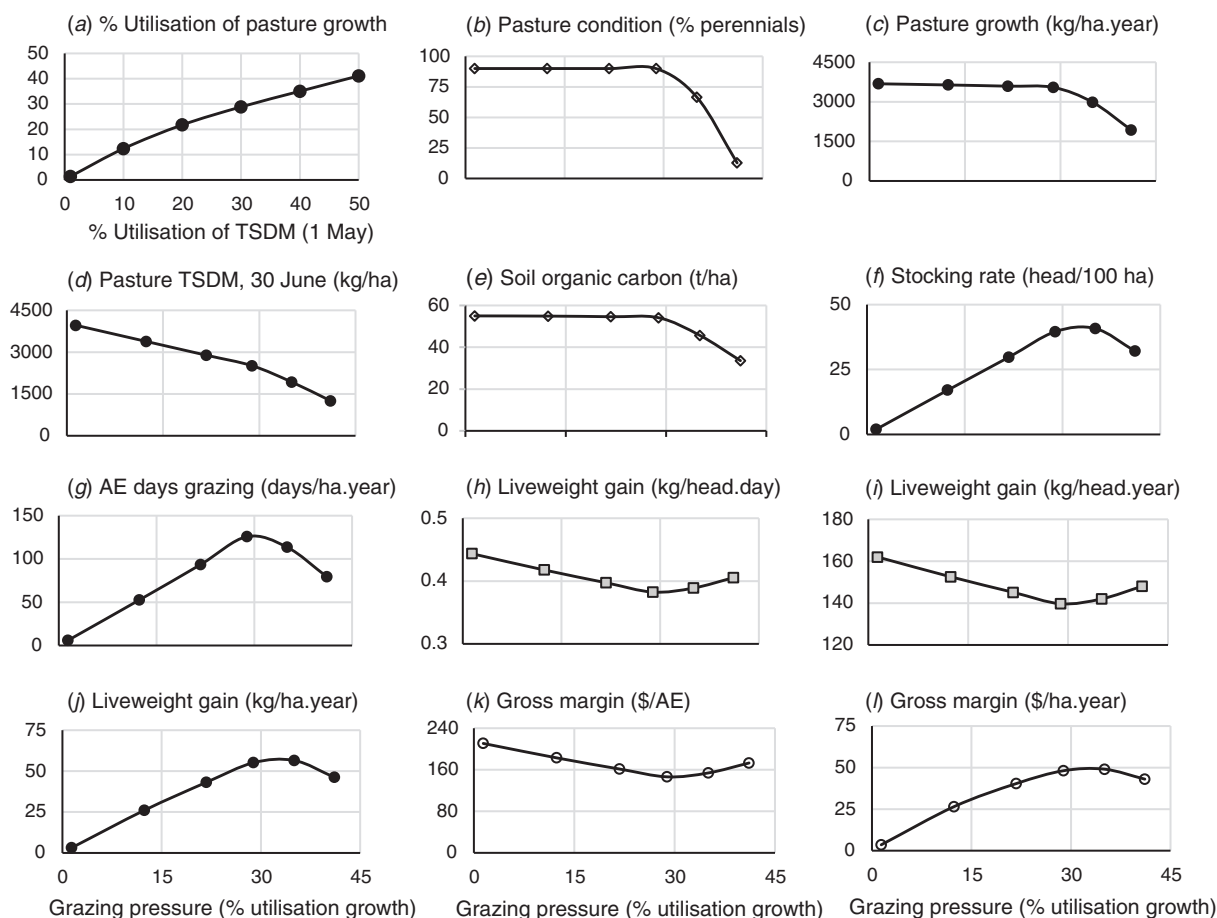


Fig. 11. Estimated effects of grazing pressure on productivity. (a) The effect of increased grazing pressure applied as 1%, 10%, 20%, 30%, 40% and 50% utilisation of TSDM at the end of the growing season (1 May) on mean annual percentage utilisation of pasture growth in the following year. All other graphs show the effects of grazing pressure (percentage utilisation of pasture growth) on mean annual pasture and cattle production, economic returns, pasture condition index (percent perennials) and soil organic carbon. All values are long-term means from 60-year GRASP simulations across the following four sites: Rehab 3, BMK3, Control and Canimbla, representing the rehab lands and the Mountain Coolibah, Brigalow Uplands and Poplar Box land types respectively.

where annual adjustments in stocking rate were based on TSDM at the end of the growing season. Maximum values of stocking rate, liveweight gain/ha and gross margin/ha occurred at 32% utilisation. Utilisation rates above 34% resulted in pastures with less than 70% perennials (B condition) because there were insufficient years for pastures to recover from losses in pasture condition caused by utilisation rates above the 35% threshold. This is consistent with Scanlan *et al.* (2010) who defined safe utilisation as being able to maintain pastures in A condition and found safe utilisation decreased with increasing aridity from 35% at Calliope (929 mm annual rainfall), to 22% at Duaringa (712 mm annual rainfall and, thus, similar to Acland) and 18% at Longreach (428 mm annual rainfall) on fertile soils. Safe utilisation rates were lower on less fertile soils and 25% utilisation guidelines are recommended for lower-fertility Box and Sandalwood land types in the Maranoa (Paton *et al.* 2011) or soils that had been eroded (Chilcott *et al.* 2004). Therefore, it follows that the previously cultivated and nutrient depleted soils of the BMK sites (Bennett *et al.* 2021)

and, more generally, across the region (McKenzie *et al.* 2017), may have safe utilisation rates lower than 30%.

The stocking rates in Table 4 derived at 30% utilisation provide estimates of sustainable ('safe') stocking rates and hence long-term carrying capacities (LTCC). These values are proportional to pasture growth and are very similar to estimates of LTCC calculated in the companion paper by Paton *et al.* (2021) where LTCC is estimated from the long-term median of annual pasture growth and an animal intake of 9 kg/AE.day. The LTCC for the rehab paddocks (36–59 AE/100 ha, Table 4) is similar to stocking rates used in the New South Wales Hunter valley region of 38 head/100 ha for rehab pastures of Rhodes grass, panic and kikuyu (Griffiths and Rose 2017), but marginally higher than LTCC estimated for buffel grass rehab pastures of 17–45 AE/100ha in central Queensland (Grigg *et al.* 2002).

The difficulty of adopting a grazing management regime in a variable climate that achieves productive returns while avoiding loss of productivity through overgrazing is well documented (McKeon *et al.* 2004; McIvor 2010). Loss of

pasture condition (and thus, productivity) is a frequent occurrence in the Darling Downs region and, more generally, in northern Australia (Tothill and Gillies 1992; Bortolussi *et al.* 2005b; Bray *et al.* 2016). Examples in the present study are the pastures in C and D condition at the BMK 10 and 11 sites and the Roundview and Mirrabooka paddocks (Table 4). Thus, future management of grazing pressure to maintain pastures in A condition is a significant ongoing challenge and residual risk to sustainable production that will require astute application of best management practices (Paton *et al.* 2011; George *et al.* 2019) with an on-going monitoring program and capacity to adjust, so that pasture condition is maintained.

General discussion

Sustainable levels of pasture and animal production have been assessed in the present paper as equal to the long-term mean of the 60-year simulations at 30% utilisation. This has many assumptions. For example, it is assumed that historical weather data are indicative of future conditions, which ignores projected influences of climate change and higher atmospheric carbon dioxide concentrations (McKeon *et al.* 2009). Rehab lands and pastures on retired cultivations are novel ecosystems (Hobbs *et al.* 2006; Buisson *et al.* 2019) and can, thus, be expected to have a range of factors causing change, including long-term changes to soil attributes and species composition. Here, it is assumed that changes in the ecosystem are limited to the effects of climate variability, pasture rundown and grazing pressure, with changes in productivity being due to pasture rundown successfully captured through changes to TSDM. However, the observed influence of pasture rundown on pasture quality (Melland *et al.* 2021; Paton *et al.* 2021) could lead to substantial long-term changes in pasture composition with reduced productivity and liveweight gain (Partridge *et al.* 2009). It is also assumed that improvements in productivity do not occur. Such improvement may occur by rebuilding soil fertility through the contribution of pastures to soil organic matter (Partridge *et al.* 2009; Sanderman *et al.* 2010; Clewett 2015; Bray *et al.* 2016) and, particularly, through use of both summer- and winter-active legumes (Peck *et al.* 2011; Paton and Clewett 2016; Whish 2017). Further development of GRASP to more adequately represent legume-based pastures, soil N availability and changes in pasture quality would be useful. Furthermore, it is assumed that the economic viability aspect of sustainability can be captured through simple gross margin analyses without reference to factors such as overhead and labour costs, cash flow and whole of enterprise issues.

The LRA map for the Central Darling Downs (Harris *et al.* 1999) shows the Acland mine area as Brigalow Uplands formed on Walloon sandstones. This parent material commonly gives rise to soils with lower P concentrations (Biggs *et al.* 1999). However, the area has a mosaic of both sandstone- and basalt-derived soils (SKM 2008; Carey 2009) and ecosystems (Sattler and Williams 1999) with a variability finer than the LRA mapping scale. The evidence of higher plant-available P concentrations in the Rehab 1 and Rehab 2 paddocks (Bennett *et al.* 2021) suggest that the topsoil for the

Rehab 1 and 2 paddocks was derived from fertile and productive softwood scrub soils of basaltic origin rather than from the less fertile soils of the Walloon sandstones. In contrast, the low plant-available P concentrations of Rehab 3 indicate that the topsoil for that paddock was probably derived from Walloon sandstones and therefore similar to soils present in the Control paddock and at BMK sites on Brigalow Uplands and Poplar Box land types. Because softwood scrub soils are not common across the mining lease, it is likely that the productivity of rehabilitated lands outside the Acland Grazing Trial paddocks is best represented by the lower productivity of Rehab 3 rather than by the higher productivity of Rehabs 1 and 2. Continuing assessments to substantiate this view would be required to develop effective grazing management plans.

Significant areas of cultivated land in the Darling Downs region are described by farmers as being 'rundown' or 'tired', and science-based assessments (Biggs 2007; Baldock *et al.* 2009; Partridge *et al.* 2009; McKenzie *et al.* 2017) have shown the region to have high levels of soil erosion, nutrient depletion and loss of soil carbon. This was also the case for sites in the Acland Land System. Bennett *et al.* (2021) found mean levels of soil organic carbon (1.4%) and total N (0.11%) for the Control and BMK sites to be less than half of the base-line levels reported by Biggs *et al.* (1999) for virgin soil profiles or grazed sites without a history of continuous cropping, and more than four times lower than carbon stocks in remnant brigalow soils (Collard and Zammit 2006; Allen *et al.* 2016). Consequently, the observed and estimated levels of sown pasture productivity reported in the present study where lands have been cultivated and cropped for over 50 years are likely to be lower than the productivity of lands that have not been cultivated and cropped for long periods.

Estimates of pasture production at paddock scale across Australia using the AussieGrass version of GRASP (Carter *et al.* 2000) are provided by the FORAGE online decision support system (Zhang and Carter 2018) on the LongPaddock website (<https://www.longpaddock.qld.gov.au/forage/>, accessed 7 October 2020; Stone *et al.* 2019) for use by industry. These estimates are based on extensive field observations, and where paddocks have been cleared of trees, the FORAGE estimates are for pastures that have completed the rundown cycle after clearing. The FORAGE estimates of median annual pasture growth of pastures in A condition on land types across the Acland Land System typically range from 3000 to 5500 kg/ha for cleared paddocks, with 3800 kg/ha as the land type mean. This mean is equivalent to the productivity estimated in the present study for the Rehab 3 pasture, much less than the productivity of the Rehab 1 and 2 pastures, and greater than the productivity of pastures on unmined but previously cultivated land. For example, the long-term mean annual pasture growth for the Brigalow Uplands land type in the Control paddock of 3169 kg/ha (estimated by GRASP in Table 4) is 23% less than the 4140 kg/ha estimate by FORAGE for the Brigalow Uplands land type in the Control paddock on the LongPaddock website (Stone *et al.* 2019). The mean across all Swiftsynd sites on unmined but previously cultivated land was 72% of the estimates on FORAGE, with the productivity

of the two pastures in C and D condition (BMK 11 and BMK 10) being reduced to 50% and 30% respectively of the FORAGE estimates. Overgrazing and poorer soil characteristics from cultivation, erosion and nutrient depletion are the likely causes of reduced productivity. Since land condition is a function of both soil condition and pasture condition, it would be appropriate to have previously cultivated lands with productivity between 45% and 75% of lands in A condition graded as equivalent to lands in B condition (Quirk and McIvor 2007; Alexander *et al.* 2018) or be identified with a new land type name (Paton *et al.* 2021). These findings show major challenges for research and industry to maintain and rebuild pasture productivity on lands retired from cultivation.

Conclusions

The integration of modelling and simulation with soil, pasture and grazing trial observations in the present study has added value to the research investment in field studies, and has also provided a useful way to assess land use suitability that includes economic viability as a component of sustainability concepts. It has evaluated effects of pasture rundown, enabled calculation of long-term carrying capacity, provided estimates of the mean and variability of rainfall use efficiency, pasture production, livestock performance and economic returns, and has enabled comparison of land types with analyses of climate risk and the risk of overgrazing to sustainable production. The two main conclusions were: (1) pastures sown on unmined cultivated lands had reduced growth with overgrazing, soil erosion, structural decline and nutrient depletion as likely causes, and (2) the rehabilitated lands at Acland provided a sustainable grazing system for economically viable beef production, although this is conditional on pastures being safely managed into the future to prevent overgrazing. Maintaining pastures in A condition will be an ongoing challenge. An effective way to mitigate this residual risk is via a pasture monitoring program and best practice grazing management that capably adjusts for pasture condition and the effects of climate variability and climate change.

Conflicts of interest

The authors declare no conflicts of interest.

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