CSIRO PUBLISHING

The Rangeland Journal, 2021, **43**, 143–157
https://doi.org/10.1071/RJ20084

An online system for calculating and delivering long-term carrying capacity information for Queensland grazing properties. Part 1: background and development

G. Stone[A,E], *B. Zhang*[A], *J. Carter*[B], *G. Fraser*[A], *G. Whish*[C], *C. Paton*[D] and *G. McKeon*[A]

[A]Grazing Land Systems, Queensland Department of Environment and Science, Brisbane, Queensland 4001, Australia.
[B]Remote Sensing Centre, Queensland Department of Environment and Science, Brisbane, Queensland 4001, Australia.
[C]Animal Science, Queensland Department of Agriculture and Fisheries, Brisbane, Queensland 4001, Australia.
[D]EcoRich Grazing, Goombungee, Queensland 4354, Australia.
[E]Corresponding author. Email: Grant.Stone@qld.gov.au

Abstract. This paper (Part 1) describes the development of a new online system that estimates long-term carrying capacity (LTCC) for grazing properties across Queensland, Australia. High year-to-year and multi-year rainfall variability is a dominating feature of the climate of Queensland's grazing lands, and poses major challenges for extensive livestock production. The use of LTCC is one approach used by graziers to reduce the impact of rainfall variability on land condition and financial performance. Over the past 30 years, scientists, graziers and their advisors have developed a simple approach to calculating LTCC ((average annual pasture growth $\times$ safe pasture utilisation) $\div$ annual animal intake). This approach has been successful at a property scale (regional south-west Queensland) and in a wider application through Grazing Land Management (GLM) regional workshops. We have built on these experiences to develop an online system (as described in detail in Part 2; Zhang *et al.* 2021; this issue) that incorporates the simple LTCC approach with advances in technology and grazing science to provide LTCC information for Queensland grazing properties. Features of the LTCC system are: (1) assimilation of spatial datasets (cadastral data, grazing land types, climate data, remotely-sensed woody vegetation cover); (2) a pasture growth simulation model; (3) land type parameter sets of biophysical attributes; and (4) estimates of safe pasture utilisation. The 'FORAGE LTCC report' is a major product of the system, describing individual property information that allows detailed analysis and explanation of the components of the LTCC calculation by land type and land condition. The online system rapidly analyses property spatial data and calculates paddock/property LTCC information. For the 10 months between November 2020 and August 2021, over 4000 grazing property reports have been requested in Queensland, and has proven to be a sound basis for 'discussion support' with grazier managers and their advisors.

Keywords: safe pasture utilisation, livestock carrying capacity, stocking rates, land condition, rainfall, pasture growth, buffel grass.

Received 21 August 2020, accepted 4 August 2021, published online 22 October 2021

Introduction

Across global and Australian rangelands, the calculation of grazing capacity or long-term carrying capacity (LTCC) has been a major challenge for grazing and resource managers (Holechek 1988; de Leeuw and Tothill 1990; Zhang *et al.* 2014; Meshesha *et al.* 2019). In general terms, LTCC is the number of animals that can be grazed without causing long-term (e.g. at multi-generational human timescales) loss of productivity of pasture and land resources. The paper describes the development of calculating and applying LTCC over the past 30 years for native pastures in northern Australia, and in particular Queensland, Australia.

Global rangelands vary in many attributes such as land tenure, infrastructure (water points, fencing), type of livestock enterprise, topography, soils, vegetation, social and regulatory control, and available land and pasture research. The online system described here is specific to Queensland's grazing industries. Nevertheless, the general goals, structure and components of the calculation of LTCC (namely pasture production, safe pasture utilisation rate, animal intake and the application to individual users) are common to most rangeland situations; hence, we use this commonality as the basis for the paper.

Since early land settlement in the 1860s, the grazing lands of Queensland have been divided into individual holdings (i.e. properties), predominantly for agricultural and livestock production. An important feature of Queensland grazing lands, compared with other global rangeland regions, is the relatively high year-to-year and multi-year variability in rainfall (e.g. Fatichi *et al.* 2012). There is also substantial spatial variation across Queensland's grazing lands with average annual rainfall decreasing from coastal to inland regions (in contrast to temporal rainfall variability increasing). Despite the resulting high temporal variability in pasture growth, Queensland grazing enterprises generally include a large nucleus/core of self-replacing flocks or herds, as well as varying degrees of trading (i.e. buying and selling) of livestock. The flexibility that grazing managers have to respond to seasonal and yearly variability in forage supply depends on: (1) long-term rainfall variability (Ash *et al.* 2000; Pahl *et al.* 2015); (2) attitude to risk (e.g. responsiveness to market fluctuations; McIvor 2010); and (3) the dependence of the enterprise on maintaining the herd/flock breeding nucleus/core (e.g. Foran and Stafford Smith 1991; McIvor 2010).

The estimation of LTCC has been an important component of grazing land settlement in Queensland since the late 19th century (Heathcote 1965). However, early government land administrators assessing viable property size and livestock managers were understandably unaware of the importance of high rainfall variability in multi-year wet and dry periods (e.g. McKeon *et al.* 2004, 2021; Stone 2004). This climatic variability has had major impacts on livestock carrying capacity, herd and flock dynamics and enterprise performance (e.g. Miller *et al.* 1973) and has led to deterioration of land and pasture condition (Weston *et al.* 1981; Tothill and Gillies 1992; McKeon *et al.* 2004). Knowledge of LTCC is important to manage for temporal rainfall variability, so as to achieve ecological sustainability (Stone 2004; O'Reagain *et al.* 2018) and financial viability (Passmore and Brown 1992). However, it is not suggested that LTCC is used as a continuous stocking rate value; but as a guide around which stock numbers can be varied seasonally/annually in order to match variability in available forage. For more risk-averse grazing managers, LTCC provides a guide that minimises the frequency of impacts of dry periods. However, a climatic feature of the grazing lands of Queensland is that extreme widespread multi-year drought conditions do occur (Day and McKeon 2018; Stone *et al.* 2019; Irvine 2021; McKeon *et al.* 2021), which still necessitate stock reduction to very low levels, even for conservatively managed properties.

Spatially, grazing for livestock is the major land use in Queensland (~85%; QDAF 2017). Extensive grazing occurs in a wide range of climatic zones (dry monsoonal, arid, semiarid, sub-tropical). Vegetation types range from treeless grasslands (Mitchell grass, *Astrebla* spp.) to open woodlands (*Eucalyptus* spp.) and edible shrublands (e.g. Mulga, *Acacia aneura*) – similarly, soils also vary considerably in texture and fertility. These native pastures also vary in land condition as a result of overgrazing in some regions (Tothill and Gillies 1992). An additional source of complexity is that there have been large areas of native pastures converted to sown grasses and legumes, with variable histories of nitrogen disturbance (e.g. tree clearing, deep ripping, blade ploughing).

As a consequence of these sources of variability, estimation of pasture productivity and associated LTCC for all locations in Queensland has been a major challenge. Over the past 30 years, this challenge has been addressed by a combination of field trials, pasture monitoring, documentation of grazier experience and regional expert consensus (Johnston *et al.* 1996*a*, 1996*b*). Since the 1940s, field experiments (i.e. grazing trials) have compared different levels of pasture utilisation or stocking rates for particular locations. The trials have demonstrated the value of conservative pasture use in managing for temporal climatic variability, and have aligned with the experience of graziers (pastoralists) with properties in benchmark condition (i.e. exhibiting stability of good land condition). Given the documented cases of grazing land degradation in Queensland (Weston *et al.* 1981; Gardener *et al.* 1990; Tothill and Gillies 1992; Ash *et al.* 2002; McKeon *et al.* 2004), the challenge has been to extrapolate scientific findings and successful grazier experiences to properties across Queensland. To be useful to individual graziers and their advisors, the calculation of LTCC needs to be accessible, transparent and specific to their own particular situation.

This paper (Part 1) describes the evolution of LTCC science in Queensland over the past 30 years and the development of a 'prototype' new online system for the rapid delivery of the FORAGE Long-Term Carrying Capacity report. This capability has been supported by advances in computing speed and capacity, and availability of spatial data (i.e. cadastral, climate, soil, grazing land types, and remote sensing of woody vegetation and ground cover). The technical detail of the online system that calculates and provides LTCC information is described in Part 2 (Zhang *et al.* 2021).

The objectives of this paper (Part 1) are to describe:

1. the background to livestock carrying capacity science and application in Queensland;
2. the development, improvements and limitations of the online LTCC calculation system;
3. the FORAGE Long-Term Carrying Capacity report;
4. the report applications and feedback; and
5. future challenges and solutions for calculating LTCC across Queensland.

Background to livestock carrying capacity science and application in Queensland

We describe the development of LTCC in Queensland through three stages since the 1990s, highlighting how the online system builds on these previous advances. We compare improvements in the components of the calculation procedure and delivery (Table 1). The major developments have occurred in a technical environment of increasing computer and remote sensing capability, but a declining availability of personnel to support on-property delivery.

Stage 1: on-property application of LTCC in south-west Queensland in the 1990s

The 'cycles' of multi-year wet and dry periods in Australia's rangelands (McKeon *et al.* 2004, 2021) led to increased livestock numbers during wet periods (e.g. early 1950s and 1970s in

Table 1. Components of long-term carrying capacity (LTCC) calculation and the developments through each stage over the past 30 years

LTCC system component	South-west Queensland (1990s)	GLM workshops (2000s)	Prototype FORAGE online LTCC report (2021)
Interaction with property owners	• On-property inspection (with grazier consultants)	• Workshop attendees and presenters	• Desktop request from Long Paddock/FORAGE webpage
Property description – land mapping and property boundary	• Land zones (15); Land systems (190); Land units (WARLUS) (Johnston *et al.* 1996*a*) • Land type mapping	• Regions (>16) • GLM Land types (>230 in Queensland) • User supplied property areas	• GLM Land types (225) • Digital cadastral database (DCDB)
Property description – paddocks and watering points	• On-property inspection • GPS for paddock boundary • Watering point locations	• Owner-supplied paddock boundaries • Watering point locations	• Paddock boundaries if supplied • Considered fully watered (unless locations supplied)
Property description – woody vegetation	• On-property inspection and 'periscope' device (150 points at 40 sites per property) for foliage projected cover (FPC; %)	• User estimated tree basal cover (TBA; $m^2\ ha^{-1}$) from photo standards or measured using a Bitterlich stick or dendrometer	• Satellite (Landsat 30 × 30 m pixels) derived FPC
Source of pasture growth parameters	• Field experiments (i.e. GUNSYNpD, SWIFTSYNpD) • Nine sites representing land systems • Five grazing trials with several years of measured aboveground biomass	• Land type parameter files developed from field measurements • Improvements from testing in regional applications (Whish *et al.* 2016) • 183 field experiments sites (i.e. GUNSYNpD, SWIFTSYNpD)	• Land type parameter files updated from previous GLM stage and testing with regional expert opinion • Recent field sites and grazing trials
Source of rainfall data	• Property rainfall supplied (if available)	• Rainfall from pre-selected BoM rainfall reporting station using the SILO database	• Rainfall from SILO climate database using input of latitude and longitude
Pasture growth simulation from GRASP	• Average annual pasture growth from GRASP was converted to Rainfall Use Efficiency (RUE) for nine land systems • These RUEs were used to construct a multiple regression using inputs of soil attributes to extrapolate to 190 land systems	• Median annual pasture growth simulated by GRASP using land type parameter sets of soil and pasture attributes	• Median annual pasture growth simulated by GRASP using land type parameter sets • RUEs calculated and included in the FORAGE LTCC report as a simple explanation to aid understanding of pasture growth estimates
Models of competition and beneficial effects of woody vegetation on pasture growth	• Pasture growth discounted as a function of FPC • Discount equation derived from field measurements • Calculation of livestock supported by mulga leaf fall (where applicable)	• The GRASP model simulates competition for water and nutrients • Nutrient and water use by woody vegetation calculated as a function of tree basal area	• The GRASP model simulates competition for water and nutrients so as to represent the Scanlan and Burrows (1990) general equation • Nutrient and water use by woody vegetation calculated as a function of FPC • Calculation of livestock supported by mulga leaf fall (where applicable)
Effect of land condition on pasture growth	• Only tree and shrub cover were used as an indicator of land condition • Discount on pasture growth is described above	• Land condition ('A', 'B', 'C', 'D') is described for land types applicable to workshop region • Discounts are applied to simulated pasture growth provided for LTCC calculation	• General land condition ('A', 'B', 'C,' 'D') is described in the FORAGE LTCC report • Discounts are applied to simulated pasture growth for LTCC calculations for 'B', 'C', 'D' land condition (AE, ha AE^{-1}) and are provided in PDF report and accessory files
Source of estimates of safe pasture growth utilisation	• Five grazing trials, three benchmark properties and expert consensus for 15 land zones	• Previous studies and updated grazing trials, benchmark properties and expert consensus for each land type (>230 in Queensland) in each region	• Previous studies and updated grazing trials, benchmark properties and expert consensus for each land type
Other databases on LTCC information	• Queensland Lands Department • Benchmark and on-property testing	• Expert opinion in development of safe utilisation rates	• Australian Bureau of Statistics livestock census and surveys • Historical livestock surveys

(*Continued*)

Table 1. (Continued)

LTCC system component	South-west Queensland (1990s)	GLM workshops (2000s)	Prototype FORAGE online LTCC report (2021)
Delivery mechanism	• On property with grazier consultants • Hardcopy report	• Workshop LTCC calculation completed by attendees, using template provided, supported by presenters	• Email delivery in response to report request on Long Paddock/ FORAGE webpage • FORAGE LTCC report (PDF) • Accessory spreadsheet files (2)
Supporting information and personnel	• Grazier consultants • Queensland State Government extension advisors, land managers and pasture scientists	• Workshop presenters • FutureBeef website information • GLM workshop manuals	• Long Paddock/FORAGE webpage: online guides, webinars, video, animations and email enquiry
User feedback	• Hardcopy survey	• Workshop evaluation and presenter assessment	• Email enquiry and feedback (yet to be conducted)
Application	• 217 properties	• 110 workshops, 73 locations (northern Australia), 1200 attendees	• 4000 reports delivered (August 2021)
Supporting publications	• Johnston *et al.* (1996*a*, 1996*b*) • Garrad and Johnston (1998) • Johnston and Garrad (1999) • Johnston *et al.* (2000)	• Quirk and McIvor (2003) • Chilcott *et al.* (2005*a*, 2005*b*) • Whish (2011) • Whish *et al.* (2016)	• Carter *et al.* (2000, 2011) • Zhang and Carter (2018) • Zhang *et al.* (2021)

Note: LTCC = (pasture growth kg DM ha^{-1} $year^{-1}$ × safe pasture utilisation %) ÷ animal intake kg $head^{-1}$ $year^{-1}$. LTCC animal units can be commonly expressed in several different forms depending on location and user (i.e. adult equivalents per paddock/property; adult equivalents per hectare; adult equivalents per 100 ha; hectares per adult equivalent).

BoM, Bureau of Meteorology; DCDB, Digital Cadastral Database (this is the Queensland State Government database of land parcels; QDNRME (2013)); FPC, Foliage Projected Cover (%; the percentage of ground area occupied by the vertical projection of the foliage of woody vegetation); GLM, Grazing Land Management (Queensland Government and Meat and Livestock Australia supported education package); GPS, Global Positioning System; GRASP, GRASs Production (a biophysical model that simulates soil water balance, nitrogen uptake, and dry matter flow (growth, senescence, detachment, decomposition, trampling and animal intake); GUNSYNpD, Grass Under Nutritional Stability: Yield, Nitrogen and phenological Development ('p' is silent; field measurement procedure to derive pasture growth parameters, harvests are 3-weekly in growing season; 6-weekly in the dry season; Day and Philp 1997); land systems, defined as areas with a recurring landform, geology, soil and vegetation pattern (Christian and Stewart 1968). Land systems are made up of land units; land units, a land system is made up of several land facets with specific landscape attributes (Gallant *et al.* 2008), which are termed land units (an older term that is now closely aligned with 'land type'); land types, a land type has characteristic patterns of soil, vegetation and landform that are easily recognised by landholders in a region (https://futurebeef.com.au/knowledge-centre/land-types-of-queensland/; RUE, Rainfall Use Efficiency (kg DM ha^{-1} mm^{-1}); SWIFTSYNpD, a more streamlined version of GUNSYNpD (four harvests per year); TBA, Tree Basal Area (m^2 ha^{-1}; a simple measurement of tree density using a Bitterlich stick); WARLUS, Western Arid Region Land Use Study (land system mapping program for south-west Queensland including soil and vegetation attributes (e.g. Dawson 1974).

south-west Queensland), followed by heavy grazing pressure when livestock have been retained in the subsequent average or dry period. Over the past 100 years, episodes of heavy grazing pressure across northern Australia resulted in native pasture deterioration and degradation (e.g. 1960s and 1980s, Miles 1990; Tothill and Gillies 1992; Mott and Tothill 1993). As a consequence, the grazing industry, resource scientists and government departments began to develop objective estimates of long-term livestock carrying capacity in order to aid graziers in managing for multi-year rainfall variability. For example, in 1988, members of the United Graziers Association (located in south-western Queensland) 'called for a critical re-evaluation of the Queensland Department of Lands rated carrying capacities: seeing the figures as subjective judgements derived in the good run of seasons in the 1950s and leading to an over-expectation of the land' (Garrad and Johnston 1998).

In developing an approach to estimate LTCC for sheep and wool enterprises in south-western Queensland, Johnston *et al.* (1996*a*) reviewed international methods for determining 'grazing capacities'. Johnston *et al.* (1996*a*) defined a 'safe' grazing capacity (i.e. LTCC) as:

> '…the number of dry sheep equivalents (DSE) that can be carried on a land system, paddock or property in the long term without any decrease in pasture condition and without accelerated soil erosion'.

Johnston *et al.* (1996*a*, 1996*b*) described the development of a system for the calculation of LTCC and application for over 200 properties in south-west Queensland. The system had several key components:

- estimation of LTCC from benchmark properties of the region (i.e. exhibiting stability of good land condition; Johnston *et al.* 1996*a*);
- accurate description of climate, land resources (i.e. soil, vegetation and landforms that are easily recognised by land managers in a region), soils and woody vegetation cover at property scale;
- pasture and soil parameters for simulation of long-term 'median' or 'average' pasture growth with the pasture model (GRASP; GRASs Production; McKeon *et al.* 2000; Rickert *et al.* 2000);
- estimates of safe pasture utilisation derived from benchmark properties, grazing trials and consensus from experienced graziers and land resource officers;
- use of on-property mapping of soils and attributes including a grazier's knowledge; and
- explanation of the LTCC calculation procedure and the results to property owners by grazier consultants.

In south-western Queensland, 217 properties were assessed from 1994 to 1998. Calculated LTCC was compared with graziers' own LTCC values: 66% of property calculated LTCCs were within ± 10% of grazier estimates; for 23% of properties, calculated LTCC was 10% (or more) below grazier estimates; and for 11% of properties, calculated LTCC was more than 10% above grazier estimates (Johnston and Garrad 1999; Johnston *et al.* 2000).

Using similar methods, approaches for estimating LTCC were developed for beef cattle enterprises utilising native pastures in north-eastern Queensland (Scanlan *et al.* 1994) and south-eastern Queensland (Day *et al.* 1997*b*). When the three studies (i.e. including Johnston *et al.* 1996*a*) were combined, the average pasture utilisation was ~20% of average annual pasture growth, with a suggested range of 15–25% (Hall *et al.* 1998). Hunt (2008) reported a similar range of values in a review of Australian pasture utilisation studies. As described below, Walsh and Cowley (2011), also found similar values for beef cattle grazing a range of pasture communities in the Northern Territory (NT).

Following Johnston *et al.* (1996*a*), the formula for calculation of LTCC is:

$$\mathrm{LTCC} = \frac{\text{area} \times \text{discount} \times \text{pasture growth} \times \text{safe pasture utilisation}}{\text{animal intake}}$$

where area is the grazed area of the property, land parcel, paddock of interest (ha); discount is the proportion of the area that is grazed considering the limitations of access to water and topography (0–1); pasture growth is median pasture growth calculated from long-term climate records (e.g. 40 years), using the pasture growth simulated from the GRASP model (kg dry matter ha^{-1} year^{-1}). The terms 'median' and 'average' have been used interchangeably in popular discourse; however, they are distinctly different mathematically, particularly for variables such as rainfall and pasture growth; safe pasture utilisation is the proportion of long-term median pasture growth that is consumed (0–100%). The value of safe pasture utilisation is derived from grazier estimates of LTCC, as well as grazing trials and regional expert opinion; and animal intake is pasture dry matter intake per head per year. For sheep, a Dry Sheep Equivalent (DSE) consumes 400 kg DM year^{-1} (i.e. 1.1 kg day^{-1}; Johnston *et al.* 1996*a*); for cattle, an adult equivalent (AE) is a 450 kg dry animal consuming 2920 kg DM year^{-1} (i.e. 8 kg DM day^{-1}; Walsh and Cowley 2011; McLennan *et al.* 2020). We recognise that a range of annual beef cattle intake values have been used in past studies for the calculation of safe utilisation rates, representing to some extent, the impact of pasture nutrition on animal consumption (e.g. 2700 kg DM AE^{-1} Hall *et al.* 1998, 3000 kg DM AE^{-1} Ash *et al.* 2002, 2920 kg DM AE^{-1} Walsh and Cowley 2011, 3650 kg DM AE^{-1} GLM rule of thumb). We follow the work of Walsh and Cowley (2011) and McLennan *et al.* 2020 to use 2920 kg DM AE^{-1} as a reasonable compromise of this uncertainty. In addition, LTCC animal units can be commonly expressed in several different forms depending on location and user (i.e. adult equivalents per paddock/property; adult equivalents per hectare; adult equivalents per 100 ha; hectares per adult equivalent).

Stage 2: Queensland-wide application through Grazing Land Management workshops

In the late 1990s, Meat and Livestock Australia (MLA; a producer-owned company, which in conjunction with the Australian government and livestock producers, delivers marketing and research programs for Australia's red meat producers), supported the production of an education package for 'grazing land management' (GLM; Anon 2002; Chilcott *et al.* 2005*c*; Quirk 2006). In 1998, MLA funded research into the types of information and package structure that potential end-users would prefer. There were also similar investigations into extension packages for nutrition and animal breeding for grazing enterprises. Following recommendations on the structure and content of a GLM training package (in 2000), courses were subsequently developed by Queensland Department of Primary Industries (QDPI) and Commonwealth Scientific Industry Research Organisation (CSIRO) staff (MLA 2002). The first GLM workshop (delivered in 2003), included a module on LTCC using the components described here as the basis for the derivation of LTCC information.

Participants in the GLM workshops were shown how to calculate LTCC from their own property description. A key component of the property description is the mapping of 'land types' for grazing. A land type has characteristic patterns of soil, vegetation and landform that are easily recognised by landholders in a region (https://futurebeef.com.au/knowledge-centre/land-types-of-queensland/). Estimation of LTCC for properties across Queensland first required identification of the land types within a region. Land types are currently derived from regional ecosystem mapping, which is largely based on overstorey floristics and aspects of soils, geology and landform (Neldner *et al.* 2020). The identification and description of regional land types involved the combination of experienced graziers and land resource scientists with relevant land resource mapping materials (e.g. Land management manuals, WARLUS, CSIRO Land Research Series; Christian and Stewart 1968; Dawson 1974).

Land type parameter sets of biophysical attributes for pasture growth modelling (Day *et al.* 1997*a*; McKeon *et al.* 2000) were developed in accordance with expert-derived estimates of LTCC (Anon. 2007; The GRASP Modelling Team 2008). The GRASP model (McKeon *et al.* 2000; Rickert *et al.* 2000) is a biophysical simulation model of soil–water balance (including evapotranspiration, runoff and drainage) and pasture dry matter flow (growth, senescence, detachment and trampling, litter decomposition and animal intake). Regional land type pasture growth estimates were then provided to participants in GLM workshops to enable them to estimate LTCC for their own properties for comparison with their own experience. Between 2002 and 2020, 110 workshops were held in over 73 locations across northern Australia, with ~1200 attendees, representing more than 700 businesses (C. Paton, unpubl. data).

As part of the GLM initiative, over 230 land type parameter sets for the GRASP model were developed for Queensland, with a further 50 currently under development for the NT (State of Queensland 2019). These land type parameter sets have enabled the simulation of long-term median pasture growth required for the calculation of LTCC at GLM workshops (Allen 2011–2019, various issues).

Since the LTCCs of properties managed by graziers were considered private, no formal assessment of comparison between the calculated LTCC and grazier experience was sought for recording purposes. Nevertheless, GLM workshop facilitators noted that participants were enthusiastic about conducting the calculation for themselves while at the workshops, which indicated the need for the further development of the LTCC system described below and in Zhang *et al.* (2021). The GLM workshop presentations and exercises also demonstrated to grazier attendees the importance of both LTCC estimates and grazing management practices such as forage budgeting.

Stage 3: development, improvements and limitations of the online LTCC calculation system

In 2015, the capability of combining pasture growth modelling and Geographical Information Systems (GIS) with digital spatial data such as property infrastructure, woody vegetation cover and land type mapping was demonstrated for 20 grazing properties in Queensland (Whish *et al.* 2016). Whish and Holloway (2016) found that estimates of LTCC could be improved through changes in model parameters to account for on-property information. Five of the 20 properties from this study provided LTCC comparisons that have been used in testing the online LTCC system (Zhang *et al.* 2021). Thus, the innovative combination of the GRASP model and GIS to calculate LTCC (Whish and Holloway 2016) provided a proof of concept for the online system described below.

Building on the above progress, the prototype online LTCC system (Zhang *et al.* 2021) is a rapid computation procedure to obtain property-level LTCC estimates for native pastures throughout Queensland. The FORAGE Long-Term Carrying Capacity report (FORAGE LTCC report, described below) provides LTCC calculations with the most recently available property description (i.e. the most recent woody vegetation cover and land type mapping). The processes, inputs and outputs, and issues to be considered are described in detail in the FORAGE LTCC report (shown below), and in Zhang *et al.* (2021).

Improvements and limitations of the online system

The calculation of LTCC and its application at property level combines a very wide range of scientific and geographical endeavour by graziers, advisors and agricultural/environmental scientists. Table 1 describes the components of LTCC calculation and the developments through each stage over the past 30 years. The three biophysical components of the calculation: LTCC = [(1) (long-term median pasture growth (kg ha^{-1} year^{-1}); (2) safe pasture utilisation (%); and (3) animal intake (kg AE^{-1} year^{-1})] have provided the focus for continual improvement through:

- field research (Hassett *et al.* 2000; Orr 2005; Phelps 2012; O'Reagain *et al.* 2014; O'Reagain *et al.* 2018; McLennan *et al.* 2020);
- development of pasture modelling (e.g. Carter *et al.* 2011; Owens *et al.* 2019) and pasture growth parameter sets for land types (Whish 2011; Whish *et al.* 2016; Zhang *et al.* 2021);
- assimilation of digital spatial datasets: land type mapping (Irvine and Holloway 2019); woody vegetation cover (Zhang *et al.* 2021); historical climate data (Jeffrey *et al.* 2001); and
- on-property evaluation (Whish *et al.* 2016; Zhang *et al.* 2021).

The major achievement of these improvements has been the capability to expand the coverage of LTCC calculation to the whole of Queensland. This expansion has been supported by the rapid advances in computing capability (from personal computers to 'high performance' computing) in combination with the databases listed above.

GRASP model development

An important factor in all three stages in the evolution of LTCC has been the use of the GRASP biophysical model to simulate pasture growth from historical daily climate data. The model has been under continual development and testing since the early 1980s (Rickert *et al.* 2000) and has been supported by field methodologies (i.e. GUNSYNpD and SWIFTSYNpD; Day and Philp 1997) to measure key parameters such as: available soil water range; potential annual nitrogen uptake; nitrogen use efficiency; potential pasture regrowth; grass basal area; and the relationship between green or total cover (Day *et al.* 1997*a*). In Queensland, the GRASP model has been calibrated for 183 native pasture field sites, as well as 10 grazing trials (Day *et al.* 1997*a*; Mayer 2013).

The capability of GRASP to simulate pasture growth for a wide range of soils and communities has been further demonstrated at an Australia-wide level (i.e. AussieGRASS; Carter *et al.* 2000, 2011). Across Australia's rangelands, the AussieGRASS version of GRASP has been parameterised for 185 native pasture communities and also for specific field locations in New South Wales, central Australia and Western Australia (McKeon *et al.* 2004). Thus, despite the complexity of soils, climate and vegetation across Queensland grazing lands, the GRASP model and its parameter sets have provided a logical basis to extrapolate to land types that have yet to be covered by field experimentation.

As discussed below, sown pastures remain a difficult issue for pasture growth estimation due to the variation in fertility (i.e. nitrogen availability) over time since initial pasture establishment. Additionally, an issue that is yet to be resolved is that only 20% (to date) of the 225 native pasture land types have supporting pasture growth field data (G. Fraser, unpubl. data). For these land types where field data are not available, land type parameter sets have been developed from the ranking of land types in terms of productivity by regional expert consensus.

Improvement in modelling interactions of woody vegetation and pasture

Woody vegetation (i.e. trees and shrubs) is an important element of rangelands and Queensland's grazing lands (Burrows *et al.* 1988). Woody vegetation has both beneficial and competitive effects on pasture growth, as well as contributing directly to animal diets (e.g. through browse and leaf litter; Johnston *et al.* 1996*a*). In the mulga woodlands, sheep and cattle consume some mulga leaf throughout the year. Johnston *et al.* (1996*a*) included a proportion of leaf fall and leaf litter in the calculation of LTCC (after Beale 1975). In the online LTCC system, this approach has been implemented for mulga land types. Other land types where browse and leaf litter make a significant component to livestock diet are yet to be identified.

For the wider application across Queensland, several approaches were considered to quantify the competitive relationship between pasture and woody vegetation. Field studies had been used to develop empirical equations between tree/shrub density (measured as tree basal area (TBA), $m^2\ ha^{-1}$) and annual pasture growth (Beale 1973; Carter and Johnston 1986; Burrows *et al.* 1990; Scanlan and Burrows 1990). Most of these equations are strongly curvilinear, reflecting the strong competitive effects of woody vegetation for water and nutrients. To address the variability in these relationships, Scanlan and Burrows (1990) combined Queensland and international studies to create a general empirical equation across a range of tree and shrub communities to calculate average annual pasture growth as a function of TBA.

The GRASP model also includes equations that represent competition between pasture and woody vegetation for water and nutrients at a daily time step (e.g. Scanlan and McKeon 1993). The model accurately simulated pasture growth at treed and cleared sites at two locations in northern Australian savannas (Day *et al.* 1997*a*; Cafe *et al.* 1999). However, wider application across Queensland land types is uncertain because of the difficulty in measuring/estimating important attributes such as: rooting depth; available water holding capacity below 1 m; size of pools of free water above impermeable layers; and variation between tree species in rooting patterns. As a consequence, a more practical approach has been used to represent the general equation of Scanlan and Burrows (1990) within the GRASP model. Thus, the current parameterisation of GRASP is consistent with the more general view of tree competition across a wider range of pasture communities.

In Stage 3, advances in remote sensing (Carter *et al.* 2011) have resulted in foliage projective cover (FPC) replacing TBA as a more useful ecophysiological measure of woody vegetation (Owens *et al.* 2019). The major source of variation in tree effects at a paddock scale is likely to be the spatial fragmentation of woody vegetation cover. To some extent, this issue is addressed in the online system by remote sensing at a high spatial resolution (i.e. 30 × 30 m) measurement of woody vegetation cover, with classification into 13 categories of FPC (Zhang *et al.* 2021).

Sub-models have also been developed in GRASP representing the beneficial effects of trees on understorey microclimate, as well as including the larger paddock scale effects of tree strips on climate elements such as wind and temperature. These developments remain the subject of current research.

Safe pasture utilisation

Published literature (e.g. Scanlan *et al.* 1994; Johnston *et al.* 1996*a*; Day *et al.* 1997*b*; Chilcott *et al.* 2005*a*, 2005*b*) and other studies (D. Phelps and P. Jones, unpubl. data), together with regional expert-derived estimates, were used to determine safe pasture utilisation levels for all land types of Queensland (G. Whish, unpubl. data). Safe pasture utilisation rates of annual pasture growth for native pastures in Queensland range between 10–30% (State of Queensland 2019), with higher rates for the more productive, resilient pastures that occur in wetter areas on fertile soils. Safe pasture utilisation rates may be higher where buffel grass (*Cenchrus ciliaris*) is dominant in pastures (State of Queensland 2019), as discussed below.

Walsh and Cowley (2011; p. 137) reviewed safe pasture utilisation rates for Queensland and their own studies in the NT. For example, they found that an average annual pasture utilisation rate of up to 25% was considered safe for uniform Mitchell grass pastures in good condition on cracking clay soils within the Barkly Tableland region of the NT. However, most importantly, they noted that such a rate impacted adversely on preferred areas where there was a mix of land types. They also observed that safe pasture utilisation rates (i.e. <15%) applied for land types of lower fertility and less resilience in other regions of the NT.

Thus, their findings support the general range of 15–25% (e.g. Hall *et al.* 1998) with fertility, mix of land types, and temporal variability in rainfall being important sources of variation in estimating safe pasture utilisation rate.

Effect of land condition on pasture growth and LTCC

The goal of calculating LTCC within the FORAGE report is to provide an LTCC estimate that would help grazing managers maintain land and pastures in the best productive state ('A' condition) for livestock through a wide range of temporal variation in rainfall. The symptoms of declining land condition (e.g. McIvor *et al.* 1995) vary with land types. Nevertheless, graziers and their advisors may be able to estimate the relative land condition of their paddocks/property from several indicators including botanical condition, ground cover, surface soil condition and animal performance. To provide a more general approach in GLM workshops, land condition is ranked from 'A' (good) to 'D' (very poor), with discounts being applied to 'A' condition pasture growth (i.e. 'B' (75%); 'C' (45%); and 'D' (20%), to show the effect on carrying capacity (after McIvor 2010).

In Stage 1 (south-west Queensland), the direct impact of woody vegetation on pasture growth was calculated; however, other aspects of declining land condition were not included in the report to graziers. In Stage 2 (i.e. GLM workshops) and the online system, woody vegetation effects are accounted for in the GRASP model through the inclusion of TBA and FPC respectively. In Stage 3, the likely effects of declining land condition are also calculated in the FORAGE LTCC report.

In the GLM workshops, there were no formal comparisons between calculated LTCC and graziers' values (as stated above). Nevertheless, the participants were very engaged in using the capability to calculate the relative benefits of improving land condition on current carrying capacity; e.g. changes from 'C' to 'A' land condition (C. Paton, unpubl. data). When possible increases in current carrying capacity were linked to the financial benefits, the impact of improving land condition took on a different perspective. For example, if a paddock's current carrying capacity was 45 AE due it being in 'C' land condition, improving the paddock to 'A' condition could increase the current carrying capacity to 100 AE. Workshop participants acknowledged that the calculations of LTCC and discounts for the effects of varying land condition were worthwhile; the potential benefits of improving land condition could then be performed through economic analysis (e.g. McLean *et al.* 2020). This observation supports the value of performing LTCC calculations, especially for estimating the relative effects of improving pasture condition; despite the known uncertainties and difficulties in the overall calculation process.

Human involvement in delivery and explanation

The online LTCC system necessarily has less human involvement in the delivery and explanation of the calculation of LTCC in comparison to previous stages (Table 1). The success in south-west Queensland and in the GLM workshops was in the ability of the consultants and presenters to interact with participants to explain the results and receive feedback, and hence improve components of the calculation (e.g. Whish *et al.* 2016).

Johnston *et al.* (1996*b*) put considerable effort into testing their LTCC model on individual properties, using grazier consultants who were involved in detailed training and assessing their own properties to develop skills and confidence. From their review and feedback, refinements were made to account for factors affecting pasture production, including woody vegetation cover and 'run-on' on flood plains. Grazier consultants reported that more accurate land system/land unit (see Table 1) mapping at property scale would improve the accuracy of LTCC estimates.

The online LTCC system provides objective property-level information rapidly. However, the number of personnel previously required to support on-property evaluation and model improvements in applications are not readily available for the Queensland-wide approach. Nevertheless, the automated system enables on-going improvement of modelling framework through additional field data and user feedback and evaluation. The users of the prototype FORAGE LTCC report include land managers, extension providers, Natural Resource Management (NRM) groups, consultant services and educational facilities, who have also been providing feedback to improve the system.

The role of GLM workshops

The previous GLM workshops (over 3 days) provided a structured interaction between presenters and participants, including a worked example of LTCC for each individual's property. A finding from the GLM workshops was that LTCC calculations were unlikely to be made by participants without the support of the workshop environment. Nevertheless, participants reported that the workshop did influence subsequent management and financial decisions (C. Paton, unpubl. data). The online system would support many of the educational activities in GLM workshops, and additionally, would provide the opportunity for evaluation and improvement to the LTCC system.

Benchmark property evaluation and use of LTCC

In Zhang *et al.* (2021, fig. 6) there was reasonable agreement reported between modelled and grazier-estimated LTCCs, where 28 of the modelled LTCC estimates (out of the 43 properties) were within $\pm$ 25% of owner-provided LTCC values. The low number of LTCC estimates reflects the difficulty of collecting this information, given the issues of privacy, confidentiality and commercial-in-confidence. There are also several uncertainties that are yet to be quantified, including climatic conditions associated with the grazier estimate period, pasture resource condition, land types and land type parameters. In addition, the collection of both pasture growth measurements and benchmark estimates of LTCC to calculate safe pasture utilisation is an expensive and time-consuming process. To address these uncertainties, the engagement of the grazing community and their advisors remains a critical component of the continuing process and ownership of the LTCC methodology described here. The evaluation of user feedback will provide the opportunity to enlarge the much-needed databases of benchmark LTCCs, improved land type maps and GRASP modelling parameter sets.

My FORAGE Map web program interface for direct input of detailed property and paddock attributes

The current online system draws upon existing broadscale spatial databases for property/paddock attributes. However, more accurate estimates of LTCC require user-defined knowledge of property description. To address this issue, the new 'My FORAGE Map web program' interface is being developed (see Zhang *et al.* 2021). The interface provides the capability to describe the property and/or paddocks in detail with essential attributes that affect pasture growth and grazing management (e.g. land types, pasture species, woody cover, fencing and water points). In particular, this capability will allow the assess of the effect of grazing distribution/preference on estimates of LTCC (Walsh and Cowley 2011).

The FORAGE Long-Term Carrying Capacity report

The major output of the online system is a comprehensive report described below covering many of the aspects that the previous three stages of development showed to be necessary to provide understanding and explanations in depth. At the time of writing (August 2021), the online system is necessarily a prototype with users' feedback providing an important component to improve the elements of the LTCC calculation (Table 1). At present, the report provides the opportunity for advisors to undertake a one-on-one dialogue with users. Thus, the online system forms the basis for discussion of the implications of carrying capacity for land condition and financial performance.

The FORAGE Long-Term Carrying Capacity report is the major output of the online system, including a five-page PDF-format report and two accessory Excel spreadsheet files (see Supplementary materials, available at the journal's website). The report is requested through the FORAGE page of the Long Paddock website (https://www.longpaddock.qld.gov.au/), which provides a range of information for grazing land management (Zhang and Carter 2018). The LTCC estimates in the report can be used as a starting point for discussion with land managers and to some extent, can be customised based on their knowledge of property attributes (including land types and land condition). Requests submitted for LTCC reports are emailed to the user usually within 10–20 hours.

FORAGE LTCC report structure

The structure of the FORAGE LTCC report (see Supplementary material) is to first provide the overall summary of LTCC (page 1) and then continues with increasingly more detailed information to assist the user with explanations of the components that have been used to make the calculation. The report provides the following information:

- Page 1 of the report provides a location map and a 'Summary of estimated LTCC'. The summary displays both total livestock (in AE) and stocking density (ha AE^{-1}) values for a range of land condition classes ('A', 'B', 'C', 'D').
- Page 2 presents three time series: (1) modelled historical annual safe stocking rates and estimated LTCC for the property. As indicated above, annual stocking rates are likely to fluctuate around an estimated LTCC in response to year-to-year variation in pasture growth (time series '3' below). The stocking rate time series shows a practical approach to changing seasonal/annual stocking rates in response to variable pasture growth; (2) the historical annual and summer season rainfall graph for the requested property derived from the SILO database (www.longpaddock.qld.gov.au/silo/); and (3) the historical 12-month pasture growth (kg DM ha^{-1}) for April–March;
- Page 3 shows the LTCC calculated for each land parcel (QDNRME 2013), or paddocks if supplied as a shapefile, and land type with the four land condition classes ('A', 'B', 'C', 'D');
- Page 4 shows the median annual pasture growth for each representative land type showing the variation in pasture productivity along with the four land condition classes; and
- Page 5 provides the estimated FPC map obtained from the latest satellite-derived woody vegetation cover data for the selected area.

Each of the above components are described in further detail in Zhang *et al.* (2021).

Accessory spreadsheet files

On requesting an LTCC report, the user will also receive two accessory Excel spreadsheet files by email (in addition to the PDF report). The accessory spreadsheet files deliver detailed information at a paddock/land parcel scale as a link between the LTCC data and the user's own knowledge. This information provides a basis for the user to adjust land condition proportions and the opportunity to provide feedback from their assessment.

FORAGE LTCC report applications and feedback

In many cases, the FORAGE LTCC report will be the first contact between the user (grazier/landholder) and advisors (e.g. extension providers, consultants) regarding grazing management discussions. The online system by itself necessarily lacks this important human interaction. For example, a likely discussion point is the comparison between the estimated LTCC and the grazier's long-term property livestock numbers. The variation in the mixture of animal size, gender and age needs to be accounted for, so as to convert actual livestock numbers to total AEs. The calculation of total AEs for various herd/flock structures has been formalised in Queensland Department of Agriculture and Fisheries (QDAF) extension products such as the 'Stocktake GLM' application to facilitate this comparison.

Explanatory information including 'frequently asked questions' is also provided on the Forage page of the Long Paddock website, along with a two-page 'quick guide', and a more detailed LTCC section within the online 'Guide to using FORAGE'. In addition, the report is supported by an 'awareness' video, which is designed to provide information and guidance of the report components in 'conversational' language. Feedback and enquiries are encouraged, as they are a necessary component for improving the online system (an email address is provided on The Long Paddock website). It is envisaged that users of the FORAGE LTCC report will be surveyed after a period of time of receiving a report (e.g. 6–12 months). The goals of the survey will be three-fold: (1) evaluate the accuracy of the report components (e.g. maps of land types and FPC); (2) compare estimated LTCC to owner-defined LTCC; and

(3) determine whether the content of the report assisted users to better manage year-to-year stock numbers.

Future challenges and solutions for calculating LTCC across Queensland

In developing the online system and designing the report for wider application across Queensland, we have identified the future challenges of: (1) parameterising land types where field data are not available; (2) parameterising sown and naturalised pastures where changes in productivity are occurring relatively rapidly (5–10 years); and (3) increasing the number of benchmark properties to provide better estimates of safe pasture utilisation rates.

Sown and naturalised pastures

The three stages of the evolution of LTCC calculations (discussed above) have concentrated on native pastures, primarily because of the apparent impact of overgrazing identified in the 1980s (Weston *et al.* 1981; Tothill and Gillies 1992). Since the 1900s, there has been an increase in many non-native grasses and sown legumes (Peck *et al.* 2011); and since the 1960s, there has been a rapid increase in sown and naturalised areas of buffel grass (Walker and Weston 1990). Peck *et al.* (2011, 2017) estimated that buffel grass was 'dominant' in 5.8 million ha (including over 30 land types) and 'common' in a further 25.9 million ha. The botanical and agronomic attributes of buffel grass contribute to its potential to invade (i.e. naturalise) existing native pastures (Martin *et al.* 2015). Compared with native pasture, buffel grass pastures are highly productive, especially after woody vegetation clearing or subsequent renovation (e.g. blade ploughing). However, rundown of available soil nitrogen after clearing and overgrazing have led to a widespread decline in productivity and carrying capacity (Walker and Weston 1990; Peck *et al.* 2011, 2017). The methodology used to measure/calibrate GRASP parameters (Day *et al.* 1997*a*) was designed for native pastures, with relatively low year-to-year variability in fertility (e.g. potential nitrogen uptake). The application of this field approach to buffel grass represents a major challenge, given that a wide range of locations and management histories have to be considered, including land type, age since initial clearing and subsequent renovations, and possible over-sowing with legume species (including *Leucaena*; Peck *et al.* 2011).

While buffel grass is recognised as the major sown grass species, it is also recognised as an invasive species in native pastures (Fensham *et al.* 2013; Martin *et al.* 2015). The invasive attributes of buffel grass are likely to be exacerbated by: (1) the interaction of grazing cycles of drought and high rainfall (Fensham *et al.* 2013); and (2) by temperature increase (i.e. global warming; Martin *et al.* 2015). Thus buffel grass is a current and emerging challenge in estimating LTCC for both sown and native pasture communities. The issue has been addressed in the online LTCC system with the addition of a 'buffel grass pasture' option at the point of request. For 14 land types where buffel grass is most likely to affect LTCC, parameters have been altered to provide higher pasture growth and safe utilisation, resulting in increased LTCC values (see Zhang *et al.* 2021 for further detail).

To a lesser extent, similar issues exist with native pasture land types where woody vegetation clearing has occurred in the past 5–10 years. The online LTCC system provides the basis for a future approach to combine current field research, expert opinion, and user evaluation/feedback to detect and represent such changes in pasture productivity and carrying capacity.

Future developments in technologies to aid pasture growth measurements and modelling

There have been recent developments in field and remote sensing technologies for improving the measurements of pasture cover and biomass, and associated pasture modelling. These advances could aid the improvement of land type parameter sets, including the estimation safe utilisation rates. For example, the operational AussieGRASS model (based on GRASP; Carter *et al.* 2000, 2011) assimilates a wide range of spatial and temporal datasets (climate data, remote sensing of woody vegetation and ground cover, rapid mobile pasture assessments, pasture nitrogen concentrations, pasture biomass from historical grazing trials and exclosures). This approach has allowed parameterisation of the major pasture communities (46) and soil types across Queensland. The AussieGRASS model is used to simulate the effects of long-term climatic variability (i.e. 130 years) to evaluate the ranking of current conditions (relative to past years) and seasonal climatic risk assessment.

AussieGRASS has provided the capability to demonstrate the value of new developments and to include them in the online LTCC system. However, there are insufficient measurements of pasture growth to develop a similar capability at the finer spatial scale of land types (225 in Queensland). At present, it is unlikely that there will be sufficient measurements of pasture growth and other parameters to build an equivalent system as AussieGRASS at the land type scale. Consequentially, AussieGRASS will have to continue as the 'testbed' for demonstrating how new information sources (e.g. remote sensing of green and ground cover, surface soil moisture, pasture nitrogen concentration, pasture standing dry matter) can be integrated into pasture growth modelling. After these new information sources have been tested in AussieGRASS, they are likely to be included in the LTCC modelling system, and hence, result in more accurate estimations of pasture growth at the paddock scale.

Examples of emerging technological developments that will improve the capability of the online LTCC system to meet the above challenges are:

- Owens *et al.* (2019) showed that flux tower measurements of evapotranspiration and remote sensing of green ground cover could be used to better parameterise the soil water sub model in GRASP for a central Australian mulga woodland;
- similarly, Liu *et al.* (2019) showed how estimations of rangeland forage production (e.g. 1 ha scale) could be improved by a small unmanned aerial system combined with remote sensing of pasture cover; and
- non-destructive sampling methods using advances in measurement of yield and chemical analysis will allow scientists to capture more sites with greater frequency, which will improve parameterisation of the GRASP model (e.g. potential nitrogen uptake and attributes of land condition; Barnetson *et al.* 2020; Paton *et al.* 2021). The parameterisation of land

condition classes (McKeon *et al.* 2000) will unlock the information already available in remotely-sensed timeseries of green, ground and total cover.

The challenges listed above share the common problem of pasture growth and nitrogen uptake measurements. Field sampling with GUNSYNpD, SWIFTSYNpD methodologies (Day and Philp 1997) is expensive, time consuming and labour intensive. The next stages of development of the LTCC system are likely to benefit from the technological advances currently being demonstrated.

Future developments in assessing evidence of improved land condition through changed grazing management practices

The prevention of degradation of the rangeland resource and the loss of livestock productivity has been a global issue for centuries (Zerga 2015). For government agencies responsible for the sustainability of the grazed resource, the major issues are first, how to monitor land and pasture condition; and second, how to separate the effects of grazing management (e.g. stocking rates) from climate variability (e.g. multi-year wet and dry periods). The use of research grazing trials and the development and application of objective systems to estimate LTCC have supported/recommended more conservative use of the pasture resource. To what extent industry has adopted 'this advice' has always been difficult to measure (i.e. in terms of land condition). Nevertheless, from the viewpoint of resource outcomes, the developments in remote sensing of vegetation (woody and ground cover) and erosion features (e.g. gullies and sediment transport) are providing a comprehensive high-spatial assessment resolution of the grazed resource. This assessment supports on-ground monitoring (e.g. Land Condition Assessment Tool; Hassett 2021), as well as other tools designed to provide individual property managers assistance in decision-making (e.g. FORAGE online reports; Stocktake GLM application). However, the estimation of grazing management effects in contrast to the impacts of climate (mainly rainfall variability) remains a challenge. Simulations studies (McKeon *et al.* 2000; Scanlan *et al.* 2011; Scanlan *et al.* 2013) have provided one approach to addressing this challenge, by representing the impact of grazing on management on pasture composition, pasture cover and pasture production.

Summary and conclusion

Estimates of LTCC are an important component of property management decisions, especially with regard to the impact of multi-year wet and dry periods on grazing enterprises and resources. The LTCC estimates provide a guide for graziers around which stock numbers can be varied to match forage availability, and for more conservative managers, concentrating on reducing the impact of dry years in order to maintain or improve property land condition. Historically, government resource managers, graziers and their advisors have had difficulty in estimating LTCC, unless they have had access to successful long-term experiences. Since the 1990s, procedures and models have been developed to extrapolate the successful experience from benchmark properties. This paper has described how the on-property methods used in the 1990s in south-west Queensland have been developed for a Queensland wide application, using the latest scientific methods of pasture modelling, remote sensing technologies and online delivery system (i.e. FORAGE; Zhang *et al.* 2021).

In reviewing the basis of the online LTCC system, we found that the simple formula (pasture growth kg DM ha^{-1} year^{-1} $\times$ safe pasture utilisation %) $\div$ animal intake kg head^{-1} year^{-1}) has provided a very useful approach, despite the large spatial variability in climate, pasture communities, soils and woody vegetation cover across Queensland. The calculation of the formula's components has been underpinned by the combination of field research, grazier experience and expert opinion. The estimation of pasture growth (using the GRASP model) has been improved by field research and the development of land type parameter sets of key biophysical variables (e.g. potential nitrogen uptake, available soil water range). Improved models of competition (for water and nutrients) between pasture and woody vegetation have been developed using empirical relationships derived from field studies and physical measurements of soil water balance. The combination of data from grazing trials, benchmark properties and regional experts has allowed the estimation of safe pasture utilisation rates across Queensland. Thus, the online LTCC system represents the continuing accumulation of grazing land science and grazier experience over the last 30 years.

We found that technological advances in computing and remote sensing data acquisition have allowed the online system to overcome some of the major limitations of previous approaches. In addition, we found that previous collation of pasture growth measurements and land type parameter sets has provided the necessary base for the modelling components for the online system. The major improvement in the online system is the rapidity and ease that property data (i.e. cadastral, land type and woody cover mapping) can be analysed and included in a report, including the calculation of LTCC. Although the online system has only been operational since November 2020, it is already proving to be a logical basis for discussion support with grazier managers and their advisors.

However, knowledge of LTCC is only one component of grazing land management; tactical response to climatic extremes, especially severe droughts, will always be necessary including management of land condition recovery. The necessity and capability to change stock numbers (year-to-year) are likely to vary with region (i.e. long-term rainfall variability) and enterprise flexibility (e.g. breeding component). Livestock enterprises that are flexible enough to match the fluctuations of the market and pasture availability have the capability to vary stock numbers around LTCC. To meet this tactical need, the online LTCC system is also supported by products such as pasture budgeting (e.g. the QDAF Stocktake GLM application) and other FORAGE online reports (e.g. Ground Cover and Pasture Growth Alert reports), to allow for more informed real-time stocking rate decisions.

The calculation of LTCC for Queensland properties remains a challenging task, given the large spatial variation in topography, soils and vegetation communities, and high temporal variability in climate (especially rainfall). Thus, the online system represents an important stage in the evolution of the calculation of grazing capacity to achieve ecological sustainability and financial viability.

Conflicts of interest

Ms Giselle Whish is a Guest Associate Editor of this issue of *The Rangeland Journal* and is also a co-author of this paper. Ms Whish was blinded from the peer-review process for this manuscript before its acceptance for publication.

Acknowledgements

The study was funded by Queensland Department of Agriculture and Fisheries (QDAF) through the Drought and Climate Adaptation Program (DCAP) and Queensland Government's Queensland Reef Water Quality Program. These activities over the past 30 years have been supported by a large number of scientists, graziers, land managers and advisors (too numerous to name). We acknowledge the inspiration of Dr Peter Johnston and colleagues for demonstrating the approach described in this paper. We also thank our colleague Ken Brook for his critical advice in improving the content of the manuscript. We gratefully acknowledge the advice and suggestions from the anonymous reviewers and editors.

References

Allen, L. (2011–2019). MLA EDGEnetwork Annual Evaluation Reports. Meat and Livestock Australia, North Sydney, NSW.

Anon. (2002). 'Grazing Land Management Education Package Technical Manual.' MLA Final report (NAP3.325). (Meat and Livestock Australia: North Sydney, NSW.)

Anon. (2007). AG10: Modelling simulation to support GLM best practice. Final Report for AgSIP Activities and Projects funded under National Action Plan for Salinity and Water Quality (NAP), Natural Heritage Trust (NHT), National Landcare Program (NLP).

Ash, A. J., O'Reagain, P. J., McKeon, G. M., and Stafford Smith, M. (2000). Managing climate variability in grazing enterprises: a case study for Dalrymple Shire. *In*: 'Applications of Seasonal Climate Forecasting in Agricultural and Natural Ecosystems, The Australian Experience'. (Eds G. L. Hammer, N. Nicholls and C. Mitchell.) pp. 254–720.

Ash, A. J., Corfield, J. P., and Ksiksi, T. (2002). 'The Ecograze Project: Developing Guidelines to Better Manage Grazing Country.' (CSIRO Sustainable Ecosystems: Townsville, Qld.)

Barnetson, J., Phinn, S., and Scarth, P. (2020). Estimating Plant Pasture Biomass and Quality from UAV Imaging across Queensland's Rangelands. *Journal of Agricultural Engineering* **2**, 523–543.

Beale, I. F. (1973). Tree density effects on yields of herbage and tree components in south-west Queensland mulga scrub. *Tropical Grasslands* **7**, 35–42.

Beale, I. F. (1975). Forage intake and digestion by sheep in the mulga zone of Queensland Australia. Ph.D. Thesis, Colorado State University, CO, USA.

Burrows, W. H., Scanlan, J. C., and Anderson, E. R. (1988). Plant ecological relations in open forests woodlands and shrub lands. *In*: 'Native Pastures in Queensland: The Resources and their Management'. QI87023. (Eds W. H. Burrows, J. C. Scanlan and M. T. Rutherford.) pp. 72–90. (Queensland Department of Primary Industries, Brisbane.)

Burrows, W. H., Carter, J. O., Scanlan, J. C., and Anderson, E. R. (1990). Management of savannas for livestock production in north-east Australia: contrasts across the tree-grass continuum. *Journal of Biogeography* **17**, 503–512. doi:10.2307/2845383

Cafe, L. M., McKeon, G. M., Dyer, R. M., and Heywood, J. M. (1999). Trees compete with pastures in the semi-arid tropics of the Northern Territory. *In*: 'People and Rangelands, Building the Future. Proceedings of the 6th International Rangeland Congress'. (Eds D. Eldridge and D. Freudenberger.) (6th International Rangeland Congress Inc.: Aitkenvale, Qld.)

Carter, J. O., and Johnston, P. J. (1986). Modelling expected frequencies of fuel loads for fire at Charleville in Western Queensland. *In*: 'Proceedings of the Third Queensland Fire Research Workshop'. Gatton. pp. 53–67.

Carter, J. O., Hall, W. B., Brook, K. D., McKeon, G. M., Day, K. A., and Paull, C. J. (2000). AussieGRASS: Australian Grassland and Rangeland Assessment by Spatial Simulation. *In*: 'Applications of Seasonal Climate Forecasting in Agricultural and Natural Ecosystems—The Australian Experience'. (Eds G. Hammer, N. Nicholls and C. Mitchell.) pp. 329–349. (Kluwer Academic Press: Netherlands.)

Carter, J., Bruget, D., Henry, B., Hassett, R., Stone, G., Day, K., Flood, N., and McKeon, G. (2011). Modelling vegetation, carbon and nutrient dynamics in the savanna woodlands of Australia with the AussieGRASS model. *In*: 'Ecosystem Function in Savannas: Measurement and Modelling at Landscape to Global Scales'. (Eds M. J. Hill and N. P. Hanan.) pp. 405–422. (CRC Press: Boca Raton, FL, USA.)

Chilcott, C. R., Hamilton, J. S., Whish, G., Paton, C. J., and Johnston, P. W. (2005*a*). Grazing land management education package workshop notes – Mulga. Meat and Livestock Australia, North Sydney, NSW.

Chilcott, C. R., Sandral, C. J., Aisthorpe, J. L., Paton, C. J., and McCallum, B. S. (2005*b*). Grazing Land Management – Fitzroy Basin Version Workshop Notes. Meat and Livestock Australia, North Sydney, NSW.

Chilcott, C. R., Quirk, M. F., Paton, C. J., Nelson, B. S., and Oxley, T. (2005*c*). Development of a grazing land management education program for northern Australia's grasslands and grassy woodlands. *In*: '20th International Grassland Congress: Offered Papers'. (Eds F. P. O'Mara, R. J. Wilkins, L. 't Mannetje, D. K. Lovett, P. A. M. Rogers and T. M. Boland.) p. 793. (Wageningen Academic Publishers: Wageningen.)

Christian, C. S., and Stewart, G. A. (1968). Methodology of integrated surveys. *In*: 'Aerial Surveys and Integrated Studies: Proceedings of the Toulouse Conference'. pp. 233–280. (United Nations Educational, Scientific and Cultural Organization: Paris.)

Dawson, N. M. (1974). Land systems. *In*: 'Western Arid Region Land Use Study, Part 1. Land Resources'. Technical Bulletin No. 12. pp. 74–83. (Queensland Department of Primary Industries: Brisbane, Qld, Australia.)

Day, K. A., and McKeon, G. M. (2018). An index of summer rainfall for Queensland's grazing lands. *Journal of Applied Meteorology and Climatology* **57**, 1623–1641. doi:10.1175/JAMC-D-17-0148.1

Day, K. A., and Philp, M. W. (1997) SWIFTSYND methodology: a methodology for measuring a minimum data set for calibrating pasture and soil parameters of the pasture growth model GRASP. Appendix 3 for Final Report DAQ-124A Evaluating the Risks of Pasture and Land Degradation in Native Pastures in Queensland. Available at: https://data.longpaddock.qld.gov.au/static/publications/DAQ124A_Appendix3.pdf (accessed 19 August 2020).

Day, K. A., McKeon, G. M., and Carter, J. O. (1997*a*). Evaluating the risks of pasture and land degradation in native pasture in Queensland. Final report for Rural Industries and Research Development Corporation project DAQ124A. Available at: https://data.longpaddock.qld.gov.au/static/publications/DAQ124A_Final.pdf (accessed 19 August 2020).

Day, K. A., Scattini, W. J., and Osborne, J. C. (1997*b*). Extended carrying capacity calculations to the central Burnett region of Queensland. *In*: 'DroughtPlan – Building on Grazier Participation to Manage for Climate Variability. Climate Variability Series, Occasional Paper CV01'. (Eds D. M. Stafford Smith, J. F. Clewett, A. D. Moore, G. M. Mckeon and R. Clark.) pp. 112–119. (Land and Water Resources Research and Development Corporation: Canberra, ACT.)

de Leeuw, P. N., and Tothill, J. C. (1990). The concept of rangeland carrying capacity in sub-Saharan Africa – myth or reality. ODI Pastoral Development Network Papers 29b. (Overseas Development Institute: London, UK.)

Fatichi, S., Ivanov, V. Y., and Caporali, E. (2012). Investigating interannual variability of precipitation at the global scale: Is there a connection with seasonality? *Journal of Climate* **25**, 5512–5523. doi:10.1175/JCLI-D-11-00356.1

Fensham, R. J., Donald, S., and Dwyer, J. M. (2013). Propagule pressure, not fire or cattle grazing, promotes invasion of buffel grass *Cenchrus ciliaris*. *Journal of Applied Ecology* **50**, 138–146. doi:10.1111/1365-2664.12009

Foran, B. D., and Stafford Smith, D. M. (1991). Risk, biology and drought management strategies for cattle stations in central Australia. *Journal of Environmental Management* **33**, 17–33. doi:10.1016/S0301-4797(05)80045-3

Gallant, J. C., McKenzie, N. J., and McBratney, A. B. (2008). Chapter 3: Scale. *In*: 'Guidelines for Surveying Soil and Land Resources'. 2nd edn. (Eds N. J. McKenzie, M. J. Grundy, R. Webster and A. J. Ringrose-Voase.) pp. 27–43. (CSIRO Publishing: Melbourne.)

Gardener, C. J., McIvor, J. G., and Williams, J. C. (1990). Dry tropical rangelands: Solving one problem and creating another. *Proceedings of the Ecological Society of Australia* **16**, 279–286.

Garrad, S., and Johnston, P. W. (1998). Appraising safe carrying capacities for all properties in south west Queensland. Final project report: Project# 945078-C, Queensland Department of Primary Industries, Queensland Government.

Hall, W. B., McKeon, G. M., Carter, J. O., Day, K. A., Howden, S. M., Scanlan, J. C., Johnston, P. W., and Burrows, W. H. (1998). Climate change and Queensland's grazing lands: II. An assessment of the impact on animal production from native pastures. *The Rangeland Journal* **20**, 177–205. doi:10.1071/RJ9980177

Hassett, R. C. (2021). Land Condition Assessment Guide Version 1.0. Rural Economic Development, Department of Agriculture and Fisheries, Queensland.

Hassett, R. C., Wood, H. L., Carter, J. O., and Danaher, T. J. (2000). A field method for statewide ground-truthing of a spatial model. *Australian Journal of Experimental Agriculture* **40**, 1069–1079. doi:10.1071/EA00010

Heathcote, R. L. (1965). 'Back of Bourke: A Study of Land Appraisal and Settlement in Semi–Arid Australia.' (Melbourne University Press: Melbourne, Vic.)

Holechek, J. L. (1988). An approach for setting the stocking rate. *Rangelands* **10**, 10–14.

Hunt, L. P. (2008). Safe pasture utilisation rates as a grazing management tool in extensively grazed tropical savannas of northern Australia. *The Rangeland Journal* **30**, 305–315. doi:10.1071/RJ07058

Irvine, S. A. (2021). Mapping drought declaration areas from 1936 to 1964 for Queensland, Australia. *The Rangeland Journal* **43**, in press.

Irvine, S., and Holloway, C. (2019). Spatial Grazing Land Management Land Types of Queensland: Review and amendments (Version 5.4) – January 2019. Technical Report. Department of Agriculture and Fisheries, Queensland.

Jeffrey, S. J., Carter, J. O., Moodie, K. B., and Beswick, A. R. (2001). Using spatial interpolation to construct a comprehensive archive of Australian climate data. *Environmental Modelling & Software* **16**(4), 309–330. doi:10.1016/S1364-8152(01)00008-1

Johnston, P. W., and Garrad, S. W. (1999). Estimating livestock carrying capacities in south-west Queensland, Australia. *In*: 'People and Rangelands, Building the Future. Proceedings of the 6th International Rangeland Congress'. (Eds D. Eldridge and D. Freudenberger.) pp. 861–862. (6th International Rangeland Congress Inc.: Aitkenvale, Qld.)

Johnston, P. W., McKeon, G. M., and Day, K. A. (1996*a*). Objective 'safe' grazing capacities for southwest Queensland, Australia: development of a model for individual properties. *The Rangeland Journal* **18**, 244–258. doi:10.1071/RJ9960244

Johnston, P. W., Tannock, P. R., and Beale, I. F. (1996*b*). Objective 'safe' grazing capacities for south-west Queensland, Australia: model application and evaluation. *The Rangeland Journal* **18**, 259–269. doi:10.1071/RJ9960259

Johnston, P., McKeon, G. M., Buxton, R., Cobon, D., Day, K. A., Hall, W. B., Scanlan, J. C. (2000). Managing climatic variability in Queensland's grazing lands – new approaches. *In*: 'Applications of Seasonal Climate Forecasting in Agricultural and Natural Ecosystems—The Australian Experience'. (Eds G. Hammer, N. Nicholls and C. Mitchell.) pp. 197–226. (Kluwer Academic Press: Netherlands.)

Liu, H., Dahlgren, R. A., Larsen, R. E., Devine, S. M., Roche, L. M., O'Geen, A. T., Wong, A. J. Y., Covello, S., and Jin, Y. (2019). Estimating rangeland forage production using remote sensing data from a small unmanned aerial system (sUAS) and planetscope satellite. *Remote Sensing* **11**, 595. doi:10.3390/rs11050595

Martin, T., Murphy, H., Liedloff, A., Thomas, C., Chadès, I., Cook, G., Fensham, R., McIvor, J., and van Klinken, R. (2015). Buffel grass and climate change: a framework for projecting invasive species distributions when data are scarce. *Biological Invasions* **17**, 3197–3210. doi:10.1007/s10530-015-0945-9

Mayer, D. (2013). Improved empirical models of cattle growth, reproduction and mortality from native pastures in northern Australia. B.NBP.0641 Final Report prepared for MLA. (Meat & Livestock Australia Limited: North Sydney, NSW.)

McIvor, J. G. (2010). 'Enhancing adoption of improved grazing and fire management practices in northern Australia: synthesis of research and identification of best bet management guidelines.' Meat and Livestock Australia Final Report Project B.NBP.0579. (Meat and Livestock Australia: North Sydney, NSW.)

McIvor, J. G., Ash, A. J., and Cook, G. D. (1995). Land condition in the tropical tallgrass pasture lands 1. Effects on herbage production. *The Rangeland Journal* **17**, 69–85. doi:10.1071/RJ9950069

McKeon, G. M., Ash, A. J., Hall, W. B., and Stafford Smith, M. (2000). Simulation of grazing strategies for beef production in north–east Queensland. *In*: 'Applications of Seasonal Climate Forecasting in Agricultural and Natural Ecosystems—The Australian Experience'. (Eds G. Hammer, N. Nicholls and C. Mitchell.) pp. 227–252. (Kluwer Academic Press: Netherlands.)

McKeon, G. M., Hall, W. B., Henry, B. K., Stone, G. S., and Watson, I. W. (2004). 'Pasture Degradation and Recovery in Australia's Rangelands: Learning from History.' 256 pp. (Queensland Department of Natural Resources, Mines and Energy: Brisbane.)

McKeon, G., Stone, G., Ahrens, D., Carter, J., Cobon, D., Irvine, S., and Syktus, J. (2021). Queensland's extended Wet and Dry periods: implications for grazing enterprises and land resources. *The Rangeland Journal* **43**, in press.

McLean, I. A., Holmes, P. R., Wellington, M. J., Walsh, D. L., Paton, C. J., and Freebairn, R. D. (2020). The Australian Beef Report: 2020 Vision. Bush AgriBusiness Pty. Ltd., Toowoomba, Queensland, Australia.

McLennan, S., McLean, I., and Paton, C. (2020). Re-defining the animal unit equivalence (AE) for grazing ruminants and its application for determining forage intake, with particular relevance to the northern Australian grazing industries. Meat and Livestock Australia Limited, North Sydney, NSW.

Meat & Livestock Australia (MLA) (2002). 'Grazing land management: Education Package Technical Manual.' NAP3.325 Final Report prepared for MLA. (Meat & Livestock Australia Limited: North Sydney, NSW.)

Meshesha, D. T., Moahmmed, M., and Yosuf, D. (2019). Estimating carrying capacity and stocking rates of rangelands in Harshin District, Eastern Somali Region, Ethiopia. *Ecology and Evolution* **9**, 13309–13319. doi:10.1002/ece3.5786

Miles, R. L. (1990). The land degradation situation of the Mulga lands of south west Queensland. *In*: 'Arid Land Administrators Conference'. Charleville, 3–5 April 1990, pp. 75–86.

Miller, F. L., Alexander, G. I., and Mawson, W. F. Y. (1973). Drought in Queensland: A farm survey into the effects of the 1964–66 drought. CSIRO and Queensland Department of Primary Industries, Canberra.

Mott, J. J., and Tothill, J. C. (1993). Degradation of savanna woodlands in Australia. *In*: 'Conservation Biology in Australia and Oceania'. (Eds C. Moritz and J. Kikkawa.) pp. 115–130. (Surrey Beatty and Sons: Chipping Norton, NSW.)

Neldner, V. J., Wilson, B. A., Dillewaard, H. A., Ryan, T. S., Butler, D. W., McDonald, W. J. F., Addicott, E. P., and Appelman, C. N. (2020)

Methodology for survey and mapping of regional ecosystems and vegetation communities in Queensland. Version 5.1. Updated March 2020. Queensland Herbarium, Queensland Department of Environment and Science, Brisbane.

O'Reagain, P. J., Scanlan, J., Cowley, R., Hunt, L., and Walsh, D. (2014). Sustainable grazing management for temporal and spatial variability in north Australian rangelands – a synthesis of the latest evidence and recommendations. *The Rangeland Journal* **36**, 223–232. doi:10.1071/RJ13110

O'Reagain, P., Bushell, J., Pahl, L., and Scanlan, J. (2018). Wambiana Grazing Trial Phase 3: Stocking Strategies for Improving Carrying Capacity, Land Condition and Biodiversity Outcomes. Meat and Livestock Australia Final Report to Project B.ERM.0107. (Meat and Livestock Australia: North Sydney, NSW.)

Orr, D. (2005). Effects of stocking rate, legume augmentation, supplements and fire on animal production and stability of native pastures. Meat and Livestock Australia Final Report to Project NAP3.207. (Meat and Livestock Australia: North Sydney, NSW.)

Owens, J., Carter, J., Fraser, G., Cleverly, J., Hutley, L., and Barnetson, J. (2019). Improving evapotranspiration estimation in pasture and native vegetation models using flux tower data, remote sensing and global optimisation. *In*: '23rd International Congress on Modelling and Simulation – Supporting Evidence-Based Decision Making: The Role of Modelling and Simulation, MODSIM 2019'. (Ed. S. Elsawah.) pp. 414–420. https://mssanz.org.au/modsim2019/C6/owens.pdf

Pahl, L. I., Scanlan, J. C., Whish, G. L., Cowley, R. A., and MacLeod, N. D. (2015). Extensive beef stocking rate strategies for coping with rainfall variability. *In*: 'Proceedings of the 18th Biennial Conference of Australian Rangeland Society'. Alice Springs, NT, April 2015. (Ed. M. H. Friedel) (Australian Rangeland Society: Parkside, South Australia.)

Passmore, J. G. I., and Brown, C. G. (1992). Property size and rangeland degradation in the Queensland mulga rangelands. *The Rangeland Journal* **14**, 9–25. doi:10.1071/RJ9920009

Paton, C. J., Clewett, J. F., Melland, A. R., Newsome, T., Eberhard, J., McL Bennett, J., and Baillie, C. P. (2021). Sustainability of beef production from brigalow lands after cultivation and mining: (1) sown pasture growth and carrying capacity. *Journal of Animal Production Science*. doi:10.1071/AN20135

Peck, G., Buck, S., Hoffman, A., Holloway, C., Johnson, B., Lawrence, D. N., and Paton, C. J. (2011). Review of productivity decline in sown grass pastures. Project B.NBP.0624 Final Report. (Meat and Livestock Australia Limited: North Sydney, NSW.)

Peck, G., Buck, S., Johnson, B., and O'Reagain, J. (2017). Improving productivity of rundown sown grass pastures. Volume 1: Project overview, key findings and recommendations. Project B.NBP.0639 Final Report. (Meat and Livestock Australia Limited: North Sydney, NSW.)

Phelps, D. (2012). Best-bet practices for managing the Mitchell grasslands of Queensland: A technical guide of options for optimising animal production, profitability and land condition. Department of Employment, Economic Development and Innovation, Qld, pp. 57.

QDNRME (Queensland Department of Natural Resources, Mines and Energy) (2013). Queensland Parcel Identification Standard 2013. SIG/2013/396 Version 4.01 13/02/2018. State of Queensland.

Queensland Department of Agriculture and Fisheries (QDAF) (2017). Queensland AgTrends 2017–18, Forecasts and trends in Queensland agricultural, fisheries and forestry production State of Queensland, 2017. https://www.daf.qld.gov.au/__data/assets/pdf_file/0007/1383928/State-of-Agriculture-Report.pdf

Quirk, M. (2006). MLA Final report (NBP.221) Customising the grazing land management education workshop to the Fitzroy Basin, Northern Gulf and Queensland Murray-Darling Basin, Meat & Livestock Australia.

Quirk, M., and McIvor, J. (2003). 'Grazing Land Management: Technical Manual.' (Meat and Livestock Australia: North Sydney, NSW.)

Rickert, K. G., Stuth, J. W., and McKeon, G. M. (2000). Modelling pasture and animal production. *In*: 'Field and Laboratory Methods for Grassland and animal Production Research'. (Eds L.'t Mannetje and R. M. Jones.) pp. 29–66. (CABI Publishing: New York.)

Scanlan, J. C., and Burrows, W. H. (1990). Woody overstorey impact on herbaceous understorey in *Eucalyptus* spp. communities in central Queensland. *Austral Ecology* **15**, 191–197. doi:10.1111/j.1442-9993.1990.tb01527.x

Scanlan, J. C., and McKeon, G. M. (1993). Competitive effects of trees on pasture are a function of rainfall distribution and soil depth. *In*: 'XVII International Grassland Congress'. Palmerston North, New Zealand. (Eds D. Eldridge and D. Freudenberger.) pp. 2231–2232. (New Zealand Grassland Association: New Zealand.)

Scanlan, J. C., McKeon, G. M., Day, K. A., Mott, J. J., and Hinton, A. W. (1994). Estimating safe carrying capacities in extensive cattle grazing properties within tropical semi-arid woodlands of north-eastern Australia. *The Rangeland Journal* **16**, 64–76. doi:10.1071/RJ9940064

Scanlan, J. C., Pahl, L., Whish, G., Macleod, N., Cowley, R., and Phelps, D. G. (2011). Enhanced adoption of improved grazing and fire management practices in northern Australia: bio-economic analysis and regional assessment of management options. Final report: NBP.0578, Meat and Livestock Australia, North Sydney, NSW, pp. 90.

Scanlan, J. C., MacLeod, N. D., and O'Reagain, P. J. (2013). Scaling results up from a plot and paddock scale to a property – a case study from a long-term grazing experiment in northern Australia. *The Rangeland Journal* **35**, 193–200. doi:10.1071/RJ12084

State of Queensland (2019). Land types of Queensland. Version 3.1. Queensland Department of Agriculture and Fisheries, Brisbane, Queensland, Australia.

Stone, G. S. (2004). Analysis of grazing pressure from the long-term livestock records of two western Queensland pastoral properties. Ch 4. *In*: 'Pasture Degradation and Recovery in Australia's Rangelands: Learning from History'. (Eds G. M. McKeon, W. B. Hall, B. K. Henry, G. S. Stone, and I. W. Watson.) pp. 191–235. (Queensland Department of Natural Resources, Mines and Energy.)

Stone, G., Dalla Pozza, R., Carter, J., and McKeon, G. (2019). Long Paddock: climate risk and grazing information for Australian rangelands and grazing communities. *The Rangeland Journal* **41**, 225–232. doi:10.1071/RJ18036

The GRASP Modelling Team (2008). Improving Grazing Management using the GRASP Model. NBP.338 Final Report for Meat and Livestock Australia, North Sydney, NSW. pp. 66.

Tothill, J. C., and Gillies, C. (1992). The pasture lands of northern Australia: their condition, productivity and sustainability. Occasional Publication No. 5, Tropical Grasslands Society of Australia, Brisbane. pp. 93.

Walker, B., and Weston, E. J. (1990). Pasture development in Queensland – a success story. *Tropical Grasslands* **24**, 257–268.

Walsh, D., and Cowley, R. A. (2011). Looking back in time: can safe pasture utilisation rates be determined using commercial paddock data in the Northern Territory? *The Rangeland Journal* **33**, 131–142. doi:10.1071/RJ11003

Weston, E. J., Harbison, J., Leslie, J. K., Rosenthal, K. M., and Mayer, R. J. (1981). 'Assessment of the agricultural and pastoral potential of Queensland.' Technical Report No. 27. (Queensland Department of Primary Industries, Agriculture Branch: Brisbane, Qld.)

Whish, G. (2011). 'Land types of Queensland. Version 2.0.' Prepared by the Grazing Land Management Workshop Team. (Department of Employment, Economic Development and Innovation: Brisbane, Qld, Australia.) Available at: https://futurebeef.com.au/knowledge-centre/grazing-land-management/land-types-of-queensland/ (accessed 4 August 2020)

Whish, G., and Holloway, C. (2016). An innovative approach to derive long-term carrying capacity estimates for extensive grazing properties in Queensland. *In*: 'Proceedings of the Northern Beef Research Update

Conference'. Rockhampton, Queensland, Australia. (North Australia Beef Research Council: Rockhampton, Qld.)

Whish, G., Pahl, L., and Holloway, C. (2016). Stage 1 – NRM SPATIAL HUB – underpinning better management decisions in the Rangelands INNOV-068-SISR-DAFF. Final Report. Department of Agriculture and Fisheries, Brisbane, Queensland. Available at: http://era.daf.qld.gov.au/id/eprint/5673/.

Zerga, B. (2015). Rangeland degradation and restoration: a global perspective. *Point Journal of Agriculture and Biotechnology Research* **1**, 37–54.

Zhang, B., and Carter, J. (2018). FORAGE – An online system for generating and delivering property-scale decision support information for grazing land and environmental management. *Computers and Electronics in Agriculture* **150**, 302–311. doi:10.1016/j.compag.2018.05.010

Zhang, Y., Zhang, X., Wang, X., Liu, N., and Kan, H. (2014). Establishing the carrying capacity of the grasslands of China: a review. *The Rangeland Journal* **36**, 1–9. doi:10.1071/RJ13033

Zhang, B., Fraser, G., Carter, J., Stone, G., McKeon, G., Whish, G., and Willcocks, J. (2021). An online system for calculating and delivering long-term carrying capacity information for Queensland grazing properties. Part 2: modelling and outputs. *The Rangeland Journal* **43**, in press.