An online system for calculating and delivering long-term carrying capacity information for Queensland grazing properties. Part 2: modelling and outputs

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Abstract.   A combination of field data and models have been used to estimate long-term carrying capacity (LTCC) of domestic livestock in Queensland grazing lands. These methods have been synthesised and coupled with recent developments in science and information technology to provide a fully-automated approach of modelling LTCC through the FORAGE online system. In this study, the GRASP model was used to simulate pasture growth with parameter sets and safe pasture utilisation rates defined for 225 land types across Queensland. Distance to water points was used to assess the accessibility of pastures to livestock. Spatial analysis classified the property into unique areas based on paddock, land type and distance to water points, which estimated pasture growth, pasture utilisation and accessibility at a sub-paddock scale. Thirteen foliage projective cover (FPC) classes were used in modelling the pasture system to deal with the non-linear relationship between tree and grass interactions. As 'proof of concept', remotely-sensed individual-date green ground cover data were used to optimise the GRASP model parameters to improve the model performance, and a Monte Carlo analysis provided uncertainty estimates for model outcomes. The framework provides an efficient and standardised method for estimating LTCC. To test the system, LTCCs from 43 'benchmark' properties were compared with simulated LTCCs, and 65% of the modelled LTCCs were within ± 25% of the benchmark LTCCs. Due to uncertainties in model inputs at the property scale and in model simulation, the modelled LTCC should be used as a starting point for further refinement of actual property LTCC.

Keywords: adult equivalent, domestic livestock carrying capacity, land condition, optimisation, safe utilisation.

Introduction

Australia's northern grazing lands have one of the most variable climates in the world (Fatichi *et al.* 2012), where multi-year wet and dry periods are a major climatic feature (Henry *et al.* 2007; McKeon *et al.* 2021). Grazing enterprises operating in these regions often have difficulty in matching domestic livestock numbers to available pasture due to high year-to-year and longer-term variability in rainfall (Stone *et al.* 2019; McKeon *et al.* 2021) and pasture growth (O'Reagain *et al.* 2014). Many graziers manage the grazing pressure well in response to the variable climate; however, high livestock numbers in drought periods have resulted in land degradation, with reduced pasture growth and soil loss (McKeon *et al.* 2004).

Stocking conservatively provides a feed reserve in drought years and increased potential for pasture recovery from drought in wetter years (O'Reagain *et al.* 2014). A long-term carrying capacity (LTCC) has been advocated (Stone *et al.* 2021), which has proven to be a simple but successful mechanism to achieve long-term productivity and sustainability (Scanlan *et al.* 1994; Johnston *et al.* 1996a, 1996b; Hall *et al.* 1998; McKeon *et al.* 2009; Whish *et al.* 2016). The LTCC is generally considered to be the number of domestic livestock that a paddock or property can support (on average) over a long period (multiple decades) without causing a reduction in land condition, allowing for pasture recovery after drought and minimising the frequency of forced responses to extreme drought (O'Reagain *et al.* 2014, 2018).

The LTCC of a property is determined by several factors including long-term annual pasture growth, an estimate of safe pasture utilisation rate and an estimate of animal intake. Additionally, distance to water for domestic livestock, grazing preference, topography and woody vegetation cover also influence pasture growth and accessibility (Scanlan *et al.* 1994; Johnston *et al.* 1996*a*, 1996*b*; Hall *et al.* 1998; Hunt *et al.* 2014; Cowley *et al.* 2015). Safe pasture utilisation is defined as the percentage of annual pasture growth eaten by domestic livestock that is not likely to cause long-term resource degradation, thus allowing for recovery of pastures after drought, and is generally between 10–30%, depending on rainfall variability, fertility and pasture composition (Johnston *et al.* 1996*a*, 1996*b*; Hall *et al.* 1998; Hunt 2008). For LTCC calculations, average long-term safe utilisations have been derived initially from grazier experience and simulated pasture growth (e.g. Scanlan *et al.* 1994; Johnston *et al.* 1996*a*, 1996*b*; Hall *et al.* 1998).

Modelling approaches to derive LTCC estimates have been developed over time and in parallel with computing/technological improvements (e.g. Scanlan *et al.* 1994; Johnston *et al.* 1996*a*, 1996*b*; Hall *et al.* 1998; Whish and Holloway 2016); however, they remain labour intensive, with the potential for inaccuracies in each type of data input (e.g. multiple land/pasture type mixtures, woody vegetation cover and water points). A more efficient, robust and automated approach that uses the latest spatial datasets, pasture models and information technology, was advocated for by the grazing industry, consultants and extension officers to estimate LTCC for facilitating grazing land and stock management decisions on a Queensland-wide basis (Whish and Holloway 2016).

FORAGE (https://www.longpaddock.qld.gov.au/forage/) is an online system that provides property-scale information for grazing land and environmental management. The system interfaces with a range of datasets (e.g. climate, soils, woody vegetation cover and satellite-derived ground cover) via the Queensland Government high performance computer (HPC), performs modelling analyses and data processing, and offers reports on climate, pasture growth and ground cover (Zhang and Carter 2018). The LTCC report (e.g. Stone *et al.* 2021) is the latest product in the FORAGE suite of reports. A comprehensive synthesis of the advances in grazing land sciences and modelling over the last a couple of decades has culminated in the LTCC report.

The LTCC information obtained from the FORAGE system can be used as a starting point for discussion on grazing land management, with the capacity for users to customise components to better represent their properties. A request for an LTCC report can be submitted from the FORAGE web interface on the Long Paddock website (https://www.longpaddock.qld.gov.au/); the user is provided with the PDF report and two accessory spreadsheets when the request is completed by the FORAGE system. The FORAGE system is maintained by the Queensland Government and is a free service.

This paper describes the components and procedures used in calculating and testing the LTCC in the FORAGE system and the modelling outputs for the LTCC report. Stone *et al.* (2021) has provided the background history and development of the new Queensland-based LTCC process, and a detailed presentation of the report from the new automated online system. The LTCC report is currently only available for properties in Queensland; however, the science, technology and modelling approach used in this study could provide useful implications for other regions in Australia and across global rangeland regions.

Our paper describes development of an automated online system for calculating LTCC, that addresses the climatic and ecological complexity of Queensland's grazing lands. We describe our approach, which includes co-design through a 'prototype' version that end users can test, and how this approach addresses major knowledge gaps through user feedback and ongoing technological improvements in remote sensing and biophysical science.

Model components and FORAGE LTCC online system

The estimation of LTCC includes several major processes:
(1) geographic information system (GIS) manipulation for spatial datasets such as property/paddocks boundaries, water points, land type (area of grazing land that has characteristic patterns of soil, vegetation and landform) and foliage projective cover (FPC, a measure of woody vegetation cover);
(2) pasture growth modelling using the GRASs Production (GRASP) model (Rickert *et al.* 2000);
(3) optimisation of the pasture model parameters using remotely sensed green ground cover (research model version only);
(4) model uncertainty analyses using Monte Carlo method (El Safadi *et al.* 2015); and
(5) quality control of model outputs and verification of the modelled LTCC.

The calculation of LTCC is carried out in three stages (Fig. 1) outlined below, which includes the above processes.

LTCC calculation components and equations

The LTCC for a property of interest is calculated using an equation adapted from previous studies (Scanlan *et al.* 1994; Johnston *et al.* 1996*a*, 1996*b*; Hall *et al.* 1998) and is described in more detail in Part 1 (Stone *et al.* 2021), as follows:

$$
\begin{aligned}
&\text{LTCC (AE)} \\
&= (\text{long-term median pasture growth} \left(\text{kg DM ha}^{-1} \text{ year}^{-1} \right) \\
&\quad * \text{safe utilisation} * \text{total area} (\text{ha}) * \text{water accessibility}) \\
&\quad / \text{annual intake for an AE} \left(\text{kg DM AE}^{-1} \text{ year}^{-1} \right)
\end{aligned}
$$

where LTCC is the total number of adult equivalents (AE), which are defined as 450 kg dry cattle, walking 7 km day^{-1} on level ground (for the purpose of intake calculation, we assume 450 kg cattle consume 8 kg DM day^{-1}); total area is the area of the property or paddock of interest in hectares (ha); annual intake for an AE is set as 2920 kg DM year^{-1} (8 kg DM day^{-1}; e.g. Stone *et al.* 2021); safe utilisation is the proportion of annual pasture growth that can be consumed by domestic livestock over a long period without causing degradation (Stone *et al.* 2021 provides further details on how safe utilisation has been derived for various pasture types); water accessibility is the proportion of the property or paddock that can be accessed by domestic
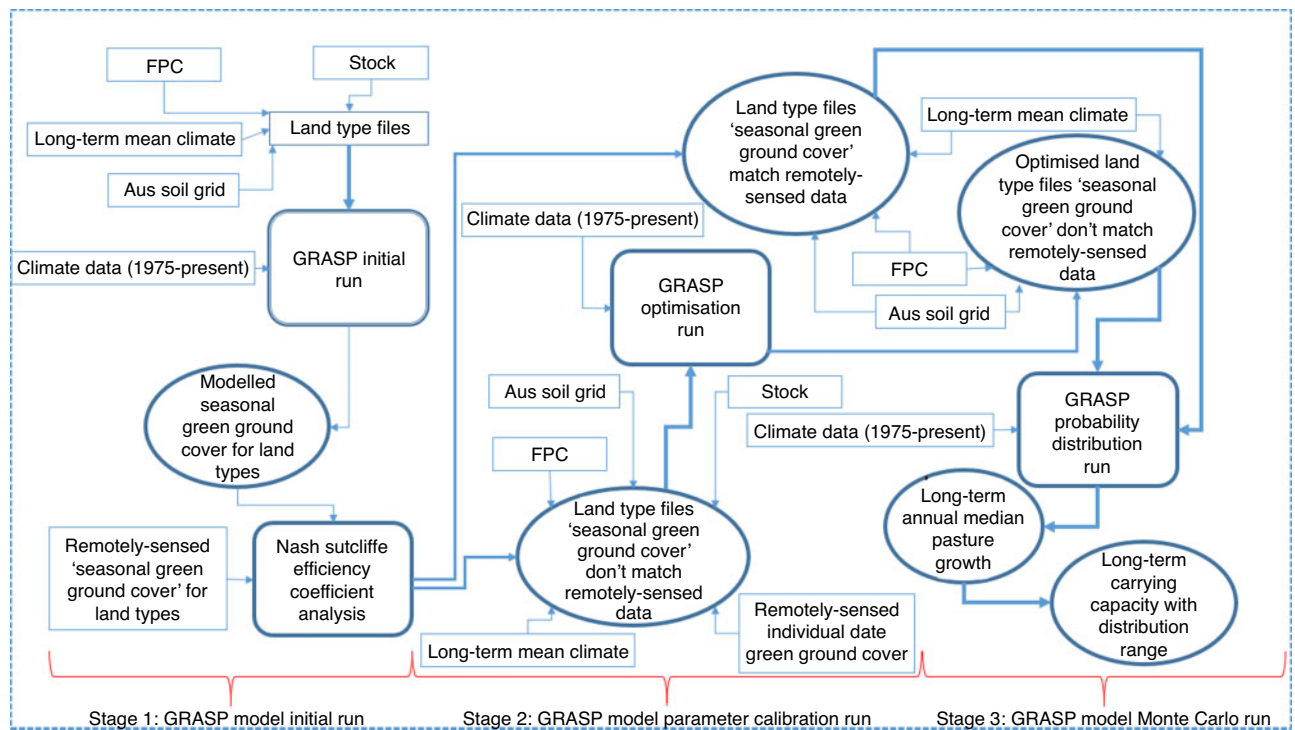
Fig. 1. The flow chart shows the three stages of using the GRASP model to calculate median pasture growth and LTCC. 'Aus soil grid' refers to the Soil and Landscape Grid of Australia and 'Stock' refers to time series of estimated livestock numbers obtained from the AussieGRASS model database.

livestock based on a function of distance to water points (Cowley *et al.* 2015).

The LTCC is calculated based on the assumption that the property is in 'A' (best) land condition (McIvor *et al.* 1995). For 'B', 'C' and 'D' land conditions, the proportions of modelled pasture growth are 0.75, 0.45 and 0.2 of the pasture growth in 'A' condition, respectively (after McIvor *et al.* 1995). These land condition states represent the overall relative impact of different biophysical degradation processes affecting infiltration, soil fertility and species composition. Users can modify the LTCC based on their knowledge of the land condition (see Stone *et al.* 2021).

The Spyglass grazing property, a Queensland Department of Agriculture and Fisheries (QDAF) Research Facility located in the Burdekin catchment of north-east Queensland, is used for an example of the calculation of LTCC in this paper.

GIS analyses

The FORAGE system uses a range of python computer programming scripts, which have been developed to use tools such as GDAL (https://gdal.org/) and MapServer (https://mapserver.org/). These tools manipulate the GIS analyses and generate maps presenting the LTCC for paddocks and land types across the property.

Property/paddock boundaries

To request an LTCC report, the user identifies their land parcel of interest by providing/selecting 'Lot(s) on Plan' from the FORAGE web interface on the Long Paddock website (https:// www.longpaddock.qld.gov.au/forage/). A 'Lot on Plan' is a consistent method for uniquely identifying land parcels in Queensland (QDNRME 2013). A paddock or property usually consists of one or more 'Lots on Plan'. A GIS vector file (e.g. shapefile) of the land parcels is then retrieved by the FORAGE system from the current Queensland Digital Cadastral Database (DCDB). Alternatively, a user can upload a file of property/ paddock boundaries using the My FORAGE Map web program interface (under development, see Stone *et al.* 2021), or draw it directly from the interface using tools provided in the program. The property/paddock boundary file is then used in the FORAGE system as a basis for the property report area (Fig. 2*a*).

Land types

A 'land type' is defined as an area of grazing land that has characteristic patterns of soil, vegetation and landform (e.g. Blackwood scrubs on structured clays), with representative pasture types (https://futurebeef.com.au/knowledge-centre/ land-types-of-queensland/). Land types are similar to the concept and scale of 'land units' within larger 'land systems' mapping (Christian and Stewart 1968; Gallant *et al.* 2008). The Grazing Land Management (GLM) land type mapping (https:// futurebeef.com.au/knowledge-centre/glm-land-type-mapping/) is the online spatial representation of the 225 land types described for Queensland. Safe annual pasture utilisation rates for each land type are provided in the State of Queensland (2019). Published literature (Scanlan *et al.* 1994; Johnston *et al.* 1996*a*, 1996*b*; Day *et al.* 1997) and unpublished studies (D. Phelps and P. Jones pers. comm.) along with other

Fig. 2.   The vector files of (*a*) property/paddocks boundaries, (*b*) land types, (*c*) distance to water points and (*d*) the composite vector file overlayed from (*a*), (*b*) and (*c*).

expert-derived estimates were used to determine the long-term mean percentage utilisation of annual pasture growth that would maintain the system in 'A' condition. Additionally, each grazing land type is represented by GRASP pasture growth parameters that allow simulation of likely year-to-year variability in pasture growth over time.

The GLM land type mapping was developed by associating land types with regional ecosystems (https://www.qld.gov.au/environment/plants-animals/plants/ecosystems), with on-going systematic review and updating of the land type spatial data (Irvine and Holloway 2019). The land type layer for the Spyglass property is shown in Fig. 2*b*.

Distance to water points

Water point information can be uploaded or drawn on the My FORAGE Map interface (in development); if no water point information is provided, it is assumed that domestic livestock have access to the entire paddock/property.

A 'distance to water points' vector file (if water point information is provided) is produced by buffering the points for 3000 m, 5000 m and >5000 m (Fig. 2*c*). Property topography (i.e. steep slopes) is also considered for the area available for grazing

by adjusting the distance to water points. A grazing discount calculation is made, where domestic livestock travelling 100 m in a vertical plane is (approximately) equivalent to travelling 900 m in a horizontal plane, with the change in elevation calculated from nearest water points (Brosh *et al.* 2010).

Vector file overlay

The above-mentioned three vector files (property boundary, land type and distance to water) are then overlayed (superimposed) to obtain a composite vector file (Fig. 2*d*), which has multiple polygons. In the composite vector, the property area is classified into small polygons; each polygon having a unique combination of paddock, land type and distance to water point. The pasture growth and LTCC are calculated for each polygon and amalgamated to estimate pasture growth and LTCC for the paddocks, land types and property.

Woody vegetation cover

Woody vegetation cover is described by an FPC raster dataset (i.e. a grid of *x* and *y* coordinates displayed on an image), with a range of 0–100%. The raster is derived from Landsat imagery by the Queensland Remote Sensing Centre (RSC) (Armston *et al.*

2002). FPC is spatially averaged and classified into 13 FPC classes (0%, 1–5%, 5–10%, 10–15%, 15–20%, 20–25%, 25–30%, 30–35% 35–45%, 45–55%, 55–65%, 65–75%, 75–100%). The FPC classes have a narrower span at the lower end of the classes where tree-grass interaction is strongly 'non-linear' (Burrows *et al.* 1990; Scanlan and Burrows 1990). The classes (rather than individual pixel values) are used to minimise FPC estimate inaccuracies and the 'computational overheads' of processing at finer scales. The proportion of each FPC class within each unique polygon (e.g. Fig. 2*d*) are then calculated and used in the GRASP model to simulate the impact of trees on pasture growth. As a comparison, FPC values of 15%, 30% and 70% equate to tree basal areas (at 1.3 m aboveground) of ~6, 12 and 32 $m^2\,ha^{-1}$ respectively (Armston *et al.* 2002).

Pasture growth modelling

The GRASP model (McKeon *et al.* 1990; Day *et al.* 1997; Carter *et al.* 2000; McKeon *et al.* 2000; Rickert *et al.* 2000) has a long history of use in Queensland and northern Australian pasture and grazing research analyses and is considered adequate to represent native pasture growth in a wide range of systems (e.g. Day *et al.* 1997; Carter *et al.* 2000). Pasture growth and biomass data and other ecological outputs have been used for over 10 years at both a property and broader spatial scale. In the context of the LTCC report, the primary GRASP model output is pasture growth; however, other model variables such as green ground cover, runoff and evapotranspiration (ET) are also produced for use in a diagnostic analysis for each land type.

Model parameters

A specialised GRASP model parameter file has been developed for each of 225 land types in Queensland. The parameter file defines the parameter values used by the GRASP model for modelling pasture growth and other outputs. The land type parameter file describes (for example) potential tree transpiration, soil water holding capacity, soil fertility and plant characteristics (such as sward structure, transpiration use efficiency, temperature response and potential nitrogen uptake and dilution). As some land types can extend over a range of ecological gradients, certain parameters are modified for local conditions. As an example, parameters relating to plant temperature response are adjusted as a function of long-term mean temperatures for that specific location; soil fertility and maximum rooting depth of trees may be adjusted higher or lower based on information obtained from the Soil and Landscape Grid of Australia (https://aclep.csiro.au/aclep/soilandlandscapegrid/).

Climate data

A historical climate dataset for the property obtained from the SILO database (https://www.longpaddock.qld.gov.au/silo/), includes data of daily temperature, rainfall, solar radiation, evaporation and vapour pressure. The climate dataset is used in the GRASP model to calculate the long-term (from 1975 onwards) median annual pasture growth. This time period is considered representative of the 'living memory' of a property manager and encompasses several 'wet and dry periods' (Stone *et al.* 2019; McKeon *et al.* 2021); and it is also well represented in the Landsat imagery record (from 1988 onwards).

Procedure for calculating LTCC: pasture growth modelling, parameter optimisation and uncertainty analyses

The three stages of the procedure to calculate LTCC are indicated in Fig. 1. At the time of writing (August 2021), *Stage 1* (initial simulation of LTCC) and *Stage 3* (uncertainty analysis) are operational. *Stage 2* (model calibration and optimisation) represents new scientific research and hence on-going evaluation occurs under operational conditions.

Stage 1: initial simulation of LTCC

Using the SILO climate data, the GRASP model is run for each land type and the 13 levels of FPC within the property. For example, if there are 10 land types within the land parcel/property, then the GRASP model is run 130 times (i.e. 10 land types × 13 FPC levels). However, not all model outputs are used in calculating pasture growth for the selected property, as properties rarely have all 13 FPC classes represented.

'GRASP model initial run' evaluates the performance of the model parameters for each land type. This is achieved by comparing the modelled seasonal green ground cover with the remotely-sensed seasonal green ground cover (i.e. satellite-derived, from the RSC), using the Nash Sutcliffe efficiency coefficient analysis (Ritter and Muñoz-Carpena 2013). The remotely-sensed seasonal green ground cover images are used instead of an 'individual-date' green ground cover to reduce the computational workload at this point of the process. There are two possible sources of variation between modelled and remotely-sensed seasonal green ground cover: (1) inaccurate estimates of green ground cover; and (2) incorrect estimates of grazing history and pasture condition changes over time.

In *Stage 1*, grazing pressure is represented using regional stocking rates obtained from the AussieGRASS model (Carter *et al.* 2000), which in turn are sourced from agricultural census and survey data collected by the Australia Bureau of Statistics (ABS) and redistributed based on elements such as available land type, pasture productivity, topography and woody vegetation cover. Land types having a low (<0) Nash Sutcliffe efficiency coefficient for modelled seasonal green ground cover are considered to not adequately represent seasonal green ground cover dynamics. 'Poor' green ground cover representation can be due to the land types being incorrectly mapped, pastures not being in 'A' condition or due to spatial variability in species composition for a particular land type. The identification of a land type not meeting the Nash Sutcliffe criterion is documented in a diagnostic report for identification, further investigation and possible parameter optimisation.

Stage 1 is based on the best available information, including land type mapping and parameters, historical climate data and operational experience with regional application of Aussie-GRASS and FORAGE products (Stone *et al.* 2019, 2021). At the time of writing (August 2021), the LTCC calculation proceeds to *Stage 3*, where the uncertainty analysis is carried out and the LTCC report is generated.

Stage 2: model calibration and optimisation

The optimisation procedure is a new development and is part of the evolving improvement in LTCC calculation (Stone *et al.* 2021). When this procedure has been fully evaluated, the

Table 1.   GRASP model parameters used which are modified during GRASP model runs for calculating of the LTCC

E, empirical models developed from AussieGRASS for model calibration; S, soil and landscape grid of Australia; O, model optimisation; M, Monte Carlo analysis

Parameter ID	Description	Method of modification
P061	If temp is less than P61, temperature index (TIX) is zero	EO
P062	As temp increases from P61 to P62, TIX increases from 0 to 1	EO
P063	As temp increases from P62 to P63, TIX remains at 1	E
P064	As temp increases from P63 to P64, TIX decreases from 1 to 0.0	E
P011	Minimum screen temperature (c) at which green cover = 0%	EO
P125	Minimum screen temperature (c) at which green cover = 100%	EO
P045	Green yield (kg ha^{-1}) when green cover for transpiration is 50%	EO
P046	Green yield (kg ha^{-1}) when radiation interception is 50%	EO
P099	Maximum N uptake (kg ha^{-1})	SM
P296	Maximum rooting depth of trees in cm	SM
P006	Potential daily regrowth rate (kg ha^{-1} day^{-1})	OM
P007	Transpiration efficiency (kg ha^{-1} mm^{-1} of pasture transpiration at vapour pressure deficit 20 hPa)	OM
P009	Soil water index allowing 100% green cover	O
P097	N uptake (kg ha^{-1}) at zero transpiration	O
P101	%N at zero growth	O
P149	Soil water index at which aboveground growth stops	O
P026	Layer 1 maximum soil moisture (mm)	M
P027	Layer 2 maximum soil moisture (mm)	M
P028	Layer 3 maximum soil moisture (mm)	MO
P029	Layer 1 wilting point soil moisture (mm)	M
P030	Layer 2 minimum soil moisture (mm)	M
P031	Layer 3 minimum soil moisture (mm)	M

process will be automatically included in the operational LTCC analysis within the FORAGE system.

In the research version of the LTCC calculation, land types that do not meet the Nash Sutcliffe green cover test enter *Stage 2* of the pasture modelling, 'GRASP model parameter calibration run' (Fig. 1). This calibration run involves applying a 'constrained model parameter optimisation process'. The cloud-free Landsat green ground cover for individual dates from 1990 to present for each land type within the property are obtained from the RSC imagery archive and are treated as 'observed' green ground cover estimates. The observed green ground cover is used to calibrate several key land type parameters in GRASP (listed in Table 1) using a 'Differential Evolution' method (Rocca *et al.* 2011).

Stage 3: uncertainty analysis

The land type parameter sets are derived from a relatively small number of pasture growth measurements and soil attributes, such as fertility and water holding capacity (Stone *et al.* 2021). To estimate the consequences of known uncertainty in key parameters, a 'modelled pasture growth uncertainty assessment' is conducted using a Monte Carlo analysis method to provide a range of estimates of pasture growth. This method randomly changes several key parameters (within constraint limits, mostly ± 30%), while also accounting for inter-parameter correlations (e.g. maximum N uptake and total water holding capacity; see Table 1). The GRASP model is run 200 times to obtain a distribution of annual median pasture growths for all the

land type and FPC combinations and resultant range of LTCC for each land type, paddock and the whole property. The mean LTCC from the Monte Carlo analyses is used as the estimated LTCC for the property, paddocks and land types with the standard deviation of the mean providing an estimated range of LTCC variation. During the Monte Carlo analysis, the GRASP model is run to simulate pasture growth without stock, but with nominal removal of biomass to avoid unrealistic build-up of ground cover.

Calculation of LTCC

For each polygon in Fig. 2*d*, the total growth for that polygon is calculated by summing up the total growth for each FPC class area in the polygon. The total growth for each FPC class area is calculated by multiplying the total area of the FPC class and the modelled long-term median annual pasture growth for the FPC class.

The quantity of total annual pasture growth (kg DM ha^{-1}) that can be safely utilised (i.e. % safe pasture utilisation) by domestic livestock (for each polygon) is calculated by multiplying the safe pasture utilisation rate of the land type (each polygon only has one land type) by the long-term median pasture growth. The resultant value may then be further discounted according to the distance of the polygon area to the nearest water points. If the distance to water points is within 3000 m, no discounting is applied; between 3000 m and 5000 m, the total annual growth is discounted by 50%; and if the distance is >5000 m, the total growth that can be consumed is set to zero as it is assumed that
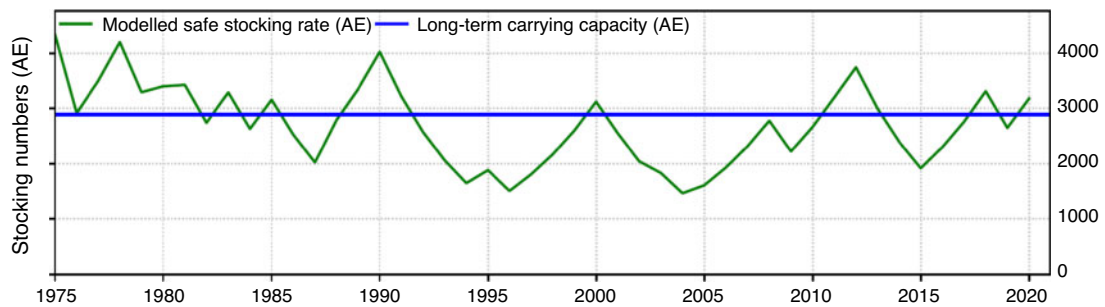
Fig. 3. An example of modelled historical annual safe stocking rate and estimated LTCC for the property (page 2 in the FORAGE LTCC report).

domestic livestock may not access the pasture within the polygon at those distances from a water point (Cowley *et al.* 2015).

By amalgamating the 'total safely eaten annual median growth' for all the polygons, the 'total safely eaten annual growth' for each paddock, each land type area and the whole property can then be determined. The final calculation of LTCC is attained by dividing the total growth of a paddock, land type or the property, with the annual intake of an AE for the paddock, land type area or property.

For land types that contain mulga (*Acacia aneura*), domestic livestock consumption of topfeed (i.e. feeding mulga leaves) is considered in the calculation of the LTCC (using FPC to calculate the topfeed available; based on Johnston *et al.* 1996*a*). To illustrate how LTCC can guide stocking rate decisions, the GRASP model is run with a set of parameters that adjust stocking rate each year according to modelled pasture growth and safe utilisation (Fig. 3).

The stocking rate graph (Fig. 3) is calculated based on a procedure developed by Scanlan *et al.* (2011) and aims to reflect practical adjustments in stocking rate around the LTCC, in response to seasonal conditions to prevent resource degradation (O'Reagain and Scanlan 2013). The first step requires the model to be run to allow calculation of the LTCC (as described above). The starting stocking rate is then set to the LTCC for the start date of 1 April 1960 (i.e. 15 years before the graph in the report). The stocking rate is then adjusted annually on 1 April. The adjustment is calculated from the annual pasture growth from the previous year; 1 April–31March. This increment in stocking rate adjustment can range from a 0–20% increase through to a 0–20% decrease depending on the annual pasture growth. Additionally, limits are applied so that the stocking rate cannot go 50% above the LTCC and cannot go 50% below the LTCC over the entire simulation.

Multi-year droughts have been a feature of Queensland's climate (e.g. Irvine 2021; McKeon *et al.* 2021) with drought episodes that have required the need for major destocking. Hence, such episodes are likely to be inevitable over a property manager's lifetime. Grazier experience (e.g. Stone 2004) and grazing trials (e.g. O'Reagain *et al.* 2018) indicate that knowledge and use of LTCC can reduce the resource and financial impact of such episodes.

An estimate of feral animal and macropod (non-domestic animal) numbers is provided in the report as a guide only, and to make the user aware that there is likely to be additional pasture

consumption by these animals. However, we do not have adequate data for non-domestic animals at the individual property scale, so these numbers are not included in the LTCC calculation; i.e. the land type safe pasture utilisation rates are only for domestic livestock.

Quality control of model outputs and model verification

For each property LTCC estimate, an internal diagnostic report is produced to assess whether the modelled results are 'acceptable', with respect to previous pasture measurements and derived empirical functions. For example, evapotranspiration and runoff are checked against the Zhang equation (Zhang *et al.* 2008); modelled green ground cover time series are checked against Landsat estimates (in research version only); the tree–grass competition is checked against functions derived from a range of field measurements in Queensland (Scanlan and Burrows 1990); and growth characteristics such as modelled actual radiation use efficiency and transpiration efficiency are checked to ensure they fall within an envelope of values (Fig. 4) derived from more than 100 field pasture growth measurements across Queensland and northern Australia (the GUNSYN$_P$D dataset; Day *et al.* 1997). Additionally, safe pasture utilisation is compared with the function derived by Hall *et al.* (1998). Growth data for non-wooded areas are used to compare the likely rankings of growth between land types and actual LTCC compared with stock estimates from ABS and other regional safe stocking rate estimates. When one of the mentioned model outputs is significantly outside of the 'normal' range for any request of LTCC, an email alert message to the FORAGE team is automatically generated to initiate investigation of any calibration and data issues.

Buffel grass impact on calculation of LTCC

The online system has been developed to calculate LTCC for properties/paddocks with native pasture land types. However, non-native buffel grass (*Cenchrus ciliaris*) is a widespread sown pasture of in >30 of the 225 land types used in the online system (e.g. Peck *et al.* 2011, 2017). Early evaluation of the online system indicated the demand for the inclusion of buffel grass impact on calculation of LTCC. The buffel grass varieties have more resilient attributes in comparison to native pasture species (Martin *et al.* 2015), such as increased pasture growth response to higher soil fertility and deeper rooting systems that allow greater tolerance to grazing and drought. These buffel grass
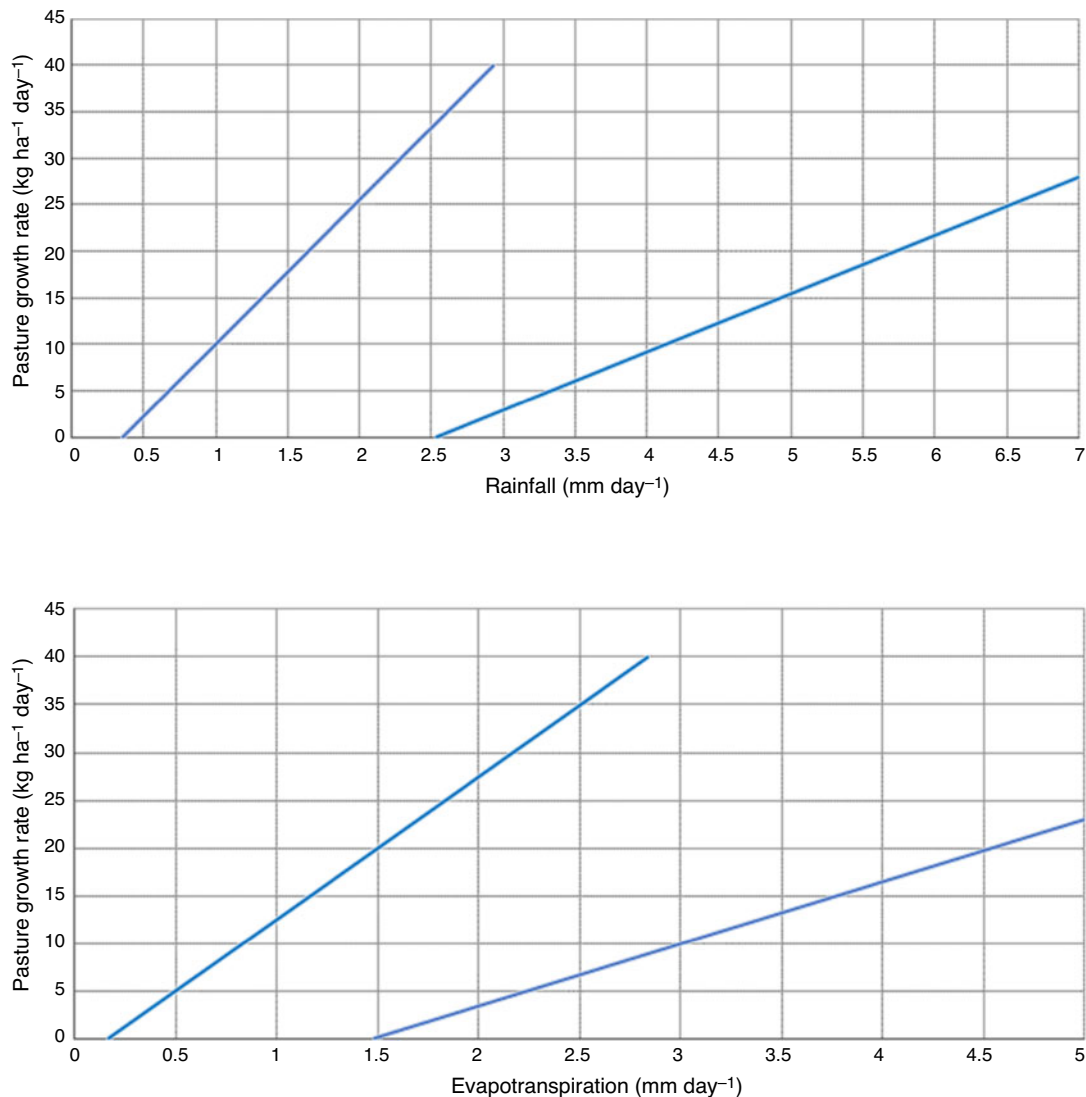
Fig. 4. An example of modelled rainfall use efficiency (top) and evapotranspiration efficiency for land type BD10 (north-east Queensland). If the dots are outside the area between the two lines, the modelling results are considered as not 'normal' and are further investigated.

attributes support higher levels of pasture utilisation by domestic livestock and animal production per head and hectare than native pastures. To address the impact of buffel grass on LTCC calculated by the online system, 14 land type parameter sets have been developed to reflect buffel grass's more productive growth and resilience. Field surveys during the period 1998–2007 (e.g. Hassett *et al.* 2000) have indicated those locations where buffel grass is likely to be dominant or common and have been cross-referenced with the 14 chosen fertile land types (Fig. 5).

To explicitly address the challenge of representing buffel grass's effects on LTCC, the online system has the following procedure. When requesting an LTCC report on the FORAGE web page, there is an option to select 'predominantly buffel grass pasture', which invokes the following three processes:

(1) If the user has selected the above option, and the land types suitable for buffel grass on the Lot on Plan have higher soil fertility and soil-water holding capacity, buffel grass land type parameter sets are used in the calculation of pasture growth. In addition, safe pasture utilisation is also increased by 15% (relative to the native pasture value).

(2) If the user has selected the above option, but the land types suitable for buffel grass on the Lot on Plan indicate lower soil fertility or low soil-water holding capacity, native pasture parameters are used to calculate pasture growth and only the safe pasture utilisation is increased by 15% (as above); and

(3) If the option is not selected, then native pasture parameters and associated safe pasture utilisation rates for that land type are used.

A major issue for buffel pasture is the rundown of available nitrogen following woodland clearing or pasture renovation (Peck *et al.* 2011, 2017). In addition, heavy pasture utilisation

based on false expectations of continuing higher productivity exacerbates the decline in pasture productivity (e.g. Peck *et al.* 2011, 2017). To address the issue of potentially overestimating LTCC, model fertility parameters have been chosen to represent the more stable rundown state. As a consequence, users who have younger pastures (i.e. where there has been recent clearing or renovation) are likely to find that the LTCC calculation underestimates their current productivity.
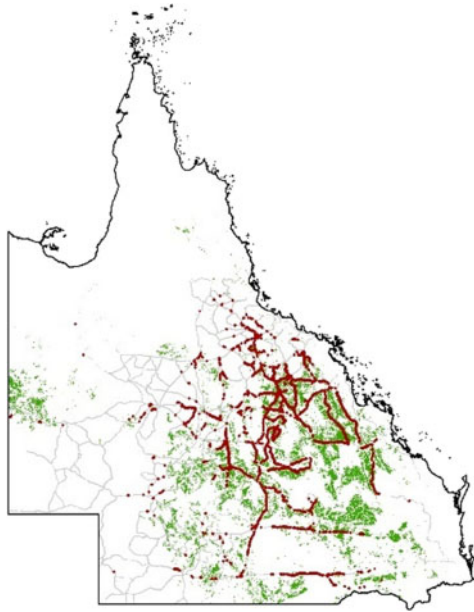

Fig. 5.   Pixels in GLM land types that are likely to be dominant in buffel grass (green shading), and observations (red tracks) from total field surveys (grey tracks) over the period 1998–2007 (e.g. Hassett *et al.* 2000). Land type parameter sets have been developed to reflect these more productive attributes.

Results

Model verification and validation

A verification/validation test of the modelled LTCC system was conducted by comparing the modelled LTCC estimates with the grazier-provided LTCC values for 43 benchmark properties across Queensland (Fig. 6). The benchmark properties were selected because they were regarded as well managed and in good (i.e. 'A') land condition. Hence, the grazier-provided LTCC values were considered as 'true' estimates of LTCC for these properties. Twenty of the benchmark properties are from the South-west Strategy project (Johnston *et al.* 1996*a*, 1996*b*) and 18 are from the Western Queensland Carrying Capacity Project, which were assessed in the mid-1990s (D. Phelps pers comm.). For a further five benchmark properties at a range of locations, LTCC values were provided by the co-authors for additional testing of the overall system. Modelling of the LTCC for all benchmark properties used approximately the same periods for the climate and FPC data as those used for the grazier estimations.

Twenty-eight (i.e. 65%) of the modelled LTCC estimates, were within ± 25% of grazier-provided LTCC values (Fig. 6). Further analysis indicated that agreement between benchmark property LTCCs and the online system LTCC calculations could be improved with the optimisation of ~20% of the land type parameter sets. This result supports the potential role of the optimisation procedure above.

The procedure used by Johnston *et al.* (1996*a*, 1996*b*) to calculate LTCC in south-west Queensland was different to the online system but had some similar components (Stone *et al.* 2021). Pasture growth was estimated from rainfall use efficiencies, which had been derived from simulations using the GRASP model, parameterised from pasture growth field studies. Safe pasture growth utilisation rates were estimated from grazing trials, benchmark properties and expert consensus (Johnston *et al.* 1996*a*). We regard the evaluation reported in
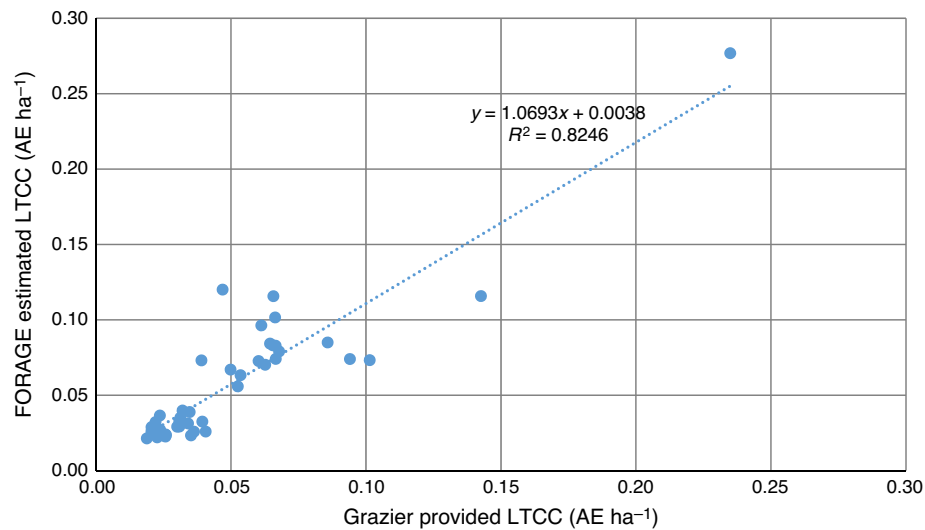

Fig. 6.   Comparison of independently FORAGE modelled LTCC (AE ha^{-1}) and grazier-provided LTCC (AE ha^{-1}) for 43 'benchmark' properties.

Fig. 6 as both a verification of the complex computing and data systems, as well as a partial independent test of the validity of the approach.

FORAGE LTCC output

The FORAGE LTCC system produces a five-page PDF report with the overall LTCC for the property of interest, with further summaries of land parcels/paddocks and land types provided (see Supplementary material, available at the journal's website). Areas considered not grazed (e.g. wetland or due to distance to water limitations) and LTCC under 'A', 'B', 'C' and

'D' condition for paddocks are summarised in a table in the report (Fig. 7). Graphical representation of the long-term historical safe stocking rate is provided in the LTCC report (Fig. 3).

Two accessory spreadsheets are also provided as a measure of transparency and to allow the user the capability to modify the base data and assess the impact of different grazing scenarios on overall property pasture condition and LTCC. One spreadsheet contains LTCC values and pasture growth data for each land parcel by land type combination; the other spreadsheet is based on land parcels/paddocks, which allows users to estimate LTCC

Long-term carrying capacity summary for paddocks/land parcels

Paddock name	Total area (ha)	Area considered not grazed (ha)	LTCC (AE) A	B	C	D	LTCC (Ha/AE) A	B	C	D
Air Strip Pdk	97.7	0.0	12	9	6	2	7.9	10.5	17.6	39.6
Arsenic Dam	13.4	0.0	0	0	0	0	−99.0	−99.0	−99.0	−99.0
Arsenic North Pdk	141.2	0.0	12	9	6	2	11.4	15.2	25.3	56.8
Arsenic Pdk	335.8	0.0	24	18	11	5	14.1	18.8	31.4	70.6
Arsenic South Pdk	118.2	0.0	16	12	7	3	7.2	9.6	16.0	36.0
Bluewater Springs Pdk	146.4	0.0	22	16	10	4	6.8	9.0	15.0	33.8
Bottom Stockyard Pdk	1061.9	0.0	120	90	54	24	8.8	11.8	19.6	44.2
Cockatoo Dam	32.9	0.0	6	4	3	1	5.7	7.5	12.6	28.3
Cockatoo Pdk	449.0	0.0	54	40	24	11	8.4	11.1	18.6	41.8
Continong Pdk	2734.3	55.9	195	146	88	39	14.0	18.7	31.2	70.1
Continong Yards	98.1	0.0	10	7	4	2	9.9	13.2	22.1	49.7
Dans Pdk	304.4	0.0	37	27	16	7	8.3	11.1	18.5	41.7
Derricks Pdk	242.4	0.0	37	28	17	7	6.5	8.6	14.4	32.4
Dingo Pdk	1366.3	0.0	102	77	46	20	13.4	17.8	29.7	66.8
Duckhole Pdk	2265.6	0.0	167	125	75	33	13.6	18.1	30.2	67.9
George Pdk	1019.9	0.0	28	21	13	6	36.0	48.0	80.0	180.1
Green Ant Dam	5.7	0.0	0	0	0	0	−99.0	−99.0	−99.0	−99.0
Green Ant Pdk	834.6	0.0	96	72	43	19	8.7	11.5	19.2	43.3
Hammers Dam	9.9	0.0	0	0	0	0	−99.0	−99.0	−99.0	−99.0
Heritage Pdk	3353.2	0.0	162	121	73	32	20.7	27.6	46.1	103.7
Homestead	109.1	0.0	9	7	4	2	11.6	15.5	25.9	58.2
Horts Dam Pdk	171.4	0.0	21	16	9	4	8.2	10.9	18.2	41.0
Howards Pdk	360.2	0.0	51	38	23	10	7.0	9.4	15.6	35.1
Junction Pdk	559.6	0.0	72	54	32	14	7.8	10.4	17.3	38.8
Little River North Pdk	133.2	0.0	25	19	11	5	5.4	7.2	11.9	26.8
Little River South Pdk	528.3	0.0	87	65	39	17	6.1	8.1	13.5	30.3
Long Pdk	32.7	0.0	5	3	2	1	7.2	9.6	16.1	36.1
Middle Yards	89.4	0.0	8	6	4	2	10.6	14.1	23.5	52.9
North Homestead Pdk	9.8	0.0	0	0	0	0	−99.0	−99.0	−99.0	−99.0
Poison Pdk	531.2	0.0	21	16	9	4	25.2	33.6	56.0	126.1
Red Pdk	363.1	0.0	16	12	7	3	22.2	29.6	49.3	111.0
Rio Tinto Dam	8.5	0.0	0	0	0	0	−99.0	−99.0	−99.0	−99.0
Rio Tinto Pdk	4614.2	0.0	226	169	102	45	20.4	27.3	45.4	102.2
River Pdk	2098.1	0.0	140	105	63	28	14.9	19.9	33.2	74.7
Roadhouse	0.9	0.0	0	0	0	0	−99.0	−99.0	−99.0	−99.0
Roadhouse Pdk	351.8	0.0	24	18	11	5	14.6	19.5	32.5	73.1
Roads Pdk	696.5	0.0	66	50	30	13	10.6	14.1	23.5	52.8
Roberts Pdk	3597.7	11.4	302	227	136	60	11.9	15.9	26.5	59.6
Rogers Pdk	326.6	0.0	11	8	5	2	30.1	40.2	67.0	150.7
Snake Creek Pdk	950.6	0.0	110	82	49	22	8.6	11.5	19.2	43.2
Soda Springs Pdk	66.5	0..0	3	2	1	1	25.4	33.9	56.5	127.1
South Homestead Pdk	77.9	0.0	9	7	4	2	8.6	11.4	19.0	42.8
South Yards	54.9	54.9	0	0	0	0	−99.0	−99.0	−99.0	−99.0
Spring Creek Pdk	2628.6	0.0	259	194	116	52	10.2	13.6	22.6	50.8
Spring Pdk	97.6	0.0	7	5	3	1	14.2	18.9	31.6	71.1
Thunder Pdk	1306.6	215.4	81	60	36	16	16.2	21.6	36.0	81.0
Top Stockyard Pdk	1560.0	0.0	157	118	71	31	9.9	13.2	22.0	49.5
Trough Pdk	112.4	0.0	6	4	2	1	20.3	27.1	45.2	101.7
Walkers Creek Pdk	1268.1	0.0	67	50	30	13	18.9	25.2	12.1	94.7
Yards	16.7	0.0	1	1	1	0	11.6	15.5	25.8	58.0
Yards Pdk	15.6	0.0	0	0	0	0	−99.0	−99.0	−99.0	−99.0
Total/mean	37369	338	2889	2167	1300	578	12.8	17.1	28.5	64.1

Fig. 7. An example of modelled LTCC for paddocks summarised into a table (page 3 in the FORAGE LTCC report). Area considered not grazed is mainly due to the area being wetland, water or 5 km away from watering source.

for land condition states other than 'A'. For more detailed information see Stone *et al.* (2021).

Diagnostic reports

An internally-used diagnostic report is also produced, which is designed for developers to assess 'model fitness'. An example of the Monte Carlo analysis is shown in Fig. 8, where the points are the LTCC values of 200 runs of the assessment. The standard deviation of the mean of the 200 runs provides a 'range of uncertainty' for the LTCC of the property of interest.

Fig. 4 shows two examples of model quality control outputs. One is the 'rainfall use efficiency' and the other is the 'evapotranspiration efficiency'. The two lines defining the areas with 'normal' values are derived from the field measurement of the GUNSYN$_P$D dataset (Day *et al.* 1997). This form of diagnostic is being improved, by considering envelope relationships derived from 30-year simulations of pasture growth to calculate rainfall, radiation and evapotranspiration use efficiencies.

Apart from the FORAGE web interface for requesting the LTCC report, all other modelling and data analyses are conducted on a Queensland Government high performance computing (HPC) server. The time taken for the computation for LTCC is ~10–20 h, depending on the complexity of the land types and other user activity on the computing framework.

Discussion

The importance of on-ground property description

There are several issues that limit the accuracy of LTCC estimates. The online system does not have the detailed descriptions of woody vegetation cover and pasture condition (e.g. dominance of feathertop grass (*Aristida latifolia*) or Indian couch (*Bothriochloa pertusa*)) that can be provided by on-ground property surveys, such as carried out by Johnston *et al.* (1996*a*, 1996*b*). The online system relies on inputs from remotely-sensed data and broad-scaled surveys that are irregularly upgraded and improved. For example, remotely-sensed digital FPC maps are not updated annually and hence, the different effects of recent clearing, fire and woody regrowth cannot be taken into consideration for the calculation of pasture growth and LTCC.

Similarly, changes in pasture type and condition have been irregularly assessed by field surveys (e.g. buffel grass and Indian couch). Users should have better knowledge of their own properties and hence can assess the implications of these inevitable uncertainties resulting from irregular input data updates. The future phases of development should address this issue by allowing users (graziers and/or advisors) to confidentially enter updated property details to better estimate LTCC for current property attributes. This issue is currently being addressed in the dynamic My FORAGE Map prototype.

The validation study indicated that 65% of properties were within ± 25% of owner-estimated LTCC with 26% within ± 10%. This variation between grazier estimates and online estimated LTCCs appears to be similar to other studies (Scanlan *et al.* 1994; Hall *et al.* 1998). However, in an evaluation survey, Johnston and Garrad (1999) found that for 217 properties, 66% of respondents reported that calculated grazier LTCC was ± 10% of respondents' expectations. In the Johnston *et al.* (1996*a*, 1996*b*) studies, there had been detailed on-ground property surveys to accurately measure inputs of land types and woody vegetation cover. Thus, while not directly comparable with the online system, this comparison nevertheless supports the importance of on-ground surveys and/or knowledge of grazier inputs to improve the calculation of LTCC.

Automation of approach

A range of modelling approaches have been used by past and current researchers, extension providers, consultants and rural land valuers to calculate the LTCC for purposes such as stocking rate assessment, infrastructure planning and property sales. The FORAGE LTCC system brings together many of the key elements of the above approaches including modelling pasture growth, applying safe utilisation of pasture growth and considering distance to water points in utilising pastures. Importantly, the FORAGE LTCC system was developed so that all stages of the modelling processes are automated to provide a transparent, efficient and standardised methodology to obtain property-level LTCC estimates on a Queensland-wide basis. The FORAGE system considerably reduces the time required to calculate the LTCC estimates for users and prevents potential errors
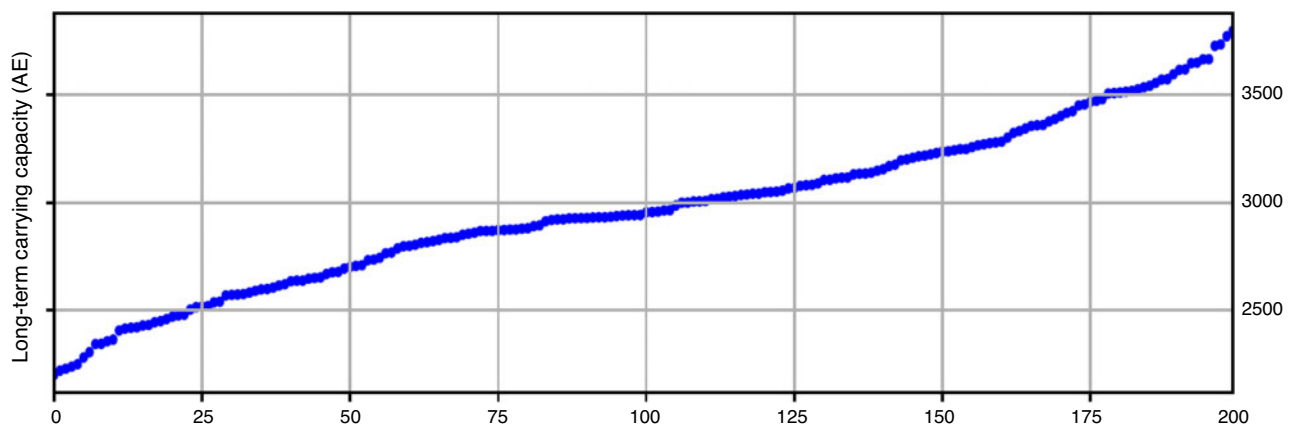

Fig. 8. An example of the LTCC distribution from the uncertainty analysis using Monte Carlo procedure. The *x*-axis is the model run number (200 model runs). The LTCCs are sorted from the lowest to the highest for best presentation.

introduced from manual or semi-automated calculations (Zhang and Carter 2018). The FORAGE online system for calculating LTCC has been operational since the November 2020; during the 10 months period, over 4000 LTCC reports requested and delivered to users.

The FORAGE system also includes research components under development (e.g. parameter optimisation with green cover, tree–grass relationships, pasture growth for sown pastures and native pastures over sown with legumes such as stylos). As the application of the online system expands to a wider range of Queensland land types, this form of 'active' research is a necessary feature of the computer-based LTCC system, which will continually evolve by using the best available information and technology, as well as incorporating feedback from users. It is recommended that development of a similar automated system for other Australian or international regions also include diagnostic assessments for continual improvement.

Optimisation of key pasture growth parameters and calculation of uncertainty

Optimisation is a common approach used to improve model performance (Papapostolou *et al.* 2011). The research version of the FORAGE LTCC system uses the remotely-sensed individual-date green ground cover (~30 years of imagery) to compare with the modelled estimate (as 'proof of concept') to optimise key GRASP model parameters, when the modelled and remotely-sensed seasonal green ground cover are not in agreement. As field data are often unavailable or minimal (both spatially and temporally), remotely-sensed green ground cover data provide a robust and reliable surrogate for field-measured ground cover (i.e. for open or lightly wooded areas), and potentially helps to improve the GRASP model parameters through optimisation. Although the GRASP model parameters for land types are well calibrated at a regional scale, variation in mesoclimate, soil and vegetation at a property scale may require the parameters to be fine-tuned to provide better agreement. The optimisation process can assist in improving the model parameters and to enhance the reliability of the modelled pasture growth at property scale. However, the optimisation process is not effective for all land type, pasture species and FPC combinations due to the complex nature of the grazing land systems. Hence the process will continue to be refined, with the aim of including it operationally in the future FORAGE LTCC system calculation.

The Monte Carlo analysis is a common method used to assess the model uncertainty caused by model parameter variation (ElSafadi *et al.* 2015). Soil features and associated water holding capacity, nitrogen availability and the pasture re-growth potential are key parameters in modelling yearly pasture growth (Day *et al.* 1997). The Monte Carlo assessment produces a range of LTCC estimations caused by likely variation of the above-mentioned parameters and allows for a quantified assessment of model output uncertainty.

Improving estimates of woody vegetation cover

The influence of trees and other woody vegetation on pasture growth is non-linear, particularly at the lower end of the woody vegetation cover scale (Scanlan *et al.* 1994). The spatial analyses used in this study classified the FPC into 13 classes and captures the FPC value at pixel scale of the FPC raster dataset (30 × 30 m). This high resolution FPC data provides detailed woody vegetation cover input for representing tree-grass competition for the GRASP modelling of pasture growth. Some limitations to using the FPC data when modelling LTCC include recent clearing and regrowth that may have occurred since the FPC data were released. In addition, at Landsat scale, there are issues in discriminating tree foliage and green grass and determining the woody/non-woody boundaries at low woody vegetation cover; a problem currently being addressed by using higher resolution imagery.

Improving land type mapping and parameters

Land type mapping and modified pastures remain an issue for producing near-accurate on-ground estimates. The modelling system's primary base is nominally a native pasture in 'A' condition. However, native perennial pastures may have been converted to another state (e.g. degraded or less productive pastures dominated by the exotic grass Indian couch, introduced/naturalised with buffel grass or planted to exotic legumes (e.g. *Stylosanthes* spp.)). As land type mapping (to a large extent) does not identify modified systems, estimates of LTCC will not reflect such transformations. However, the My FORAGE Map web interface (in development) will allow the user to adjust mapping attributes to achieve an improved property representation. Not all bio-physical processes in native pastures are fully described mathematically in the GRASP model, and some parameters may not be well determined. Nevertheless, we believe the multiple constraints approach generally gives reasonable results, and the system provides a uniformity of method across Queensland rather than variable '*ad hoc*' model parameterisations by individual users.

Land type-based model parameterisation used in the FORAGE LTCC system is calibrated at the regional scale. At the property scale, the land types and the boundaries may not always be accurate due to the complex nature and scale of mapping of the regional ecosystems. Additionally, land type parameters for regions such as the Channel Country in south-west Queensland, Northern Gulf in north Queensland, and other complex regions may not be well calibrated due to lack of primary pasture growth calibration sites. Therefore, the modelled LTCC from these particular areas should be used principally as 'discussion' material with further investigation to combine LTCC with information obtained from relevant on-ground assessment.

Annual variability in pasture growth and LTCC estimates for certain land type(s) on a property may be inaccurate for reasons such as flood-out zones or a limited understanding of the grazing system. The more 'dynamic' My FORAGE Map web interface (in development) with user-defined inputs will have more capacity to deal with these complexities.

In the future, it is envisaged that the FORAGE system will enable assessment of climate change impacts on LTCC using high resolution dynamically down-scaled and bias corrected climate data developed by the Queensland Government (https://longpaddock.qld.gov.au/qld-future-climate). Evaluation of other scenario analyses applications, such as impact of 'fencing

to land type', water point placement and paddock re-distribution are also intended within the My Forage Map web interface.

Conclusion

The automated modelling processes introduced by Stone *et al.* (2021) and described within, provide an efficient and standardised methodology to obtain property-level LTCC estimates for Queensland. The calculation of LTCC through systematic modelling approaches that simulate pasture growth for land types across Queensland, adjusted by safe utilisation rates, topography and distance to water points can be used to provide a systematic approach to estimating LTCC at a paddock or property scale across Queensland.

This automated system provides a consistent approach that is much faster than previous manual calculation methods, providing a discussion starter about LTCC, land condition and sustainable long-term planning. There are assumptions, such as native pastures being dominant and that the land is in 'A' (best) condition, which need to be considered and we recommend that some on-ground property-based knowledge and adjustments may be required for the LTCC estimates.

Conflicts of interest

Ms Giselle Whish and Ms Jacqui Willcocks are Guest Associate Editors of this Special Issue of *The Rangeland Journal* and are also co-authors of this paper. Ms Whish and Ms Willcocks were blinded from the peer-review process for this manuscript before its acceptance for publication.

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