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Northern Australian pasture and beef systems. 2. Validation and use of the Sustainable Grazing Systems (SGS) whole-farm biophysical model

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Abstract. The Sustainable Grazing Systems (SGS) model is a biophysical, mechanistic whole-farm model that simulates pasture production based on climate and soil data. While the SGS model has been extensively used for southern temperate systems, the model has yet to be evaluated for use in the tropical rangeland systems of Australia. New pasture parameter sets were developed in SGS to represent groups of grasses with the following common characteristics: (1) 3P grasses represented tropical rangeland grasses that were perennial, palatable and productive, and (2) annual tropical grasses that include both productive and less productive grass species. Fifteen years of data from the long-term Wambiana grazing trial ~70 km south-west of Charters Towers, Queensland, were used to validate the model. The results showed that SGS is capable of representing northern Australian beef systems with modelled outputs for total standing dry matter and steer liveweight in agreement with the year-to-year variation in measured data over three different soil types and two stocking rates. Recommendations for further model development are made, such as incorporating fire, tree growth and the use of urea supplementation in the model. Further testing is required to verify that the new pasture parameter sets are suitable for other regions in northern Australia.

Additional keywords: cattle, modelling, rangelands.

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Introduction

Low and declining profitability and poor productivity are impacting on the sustainability of northern Australia beef businesses (McLean *et al*. 2014). A range of principles and management guidelines have been proposed to improve beef business profitability and sustainability in northern Australia such are improving reproductive rates and managing stocking rates to meet goals for livestock production and land condition (Hunt *et al*. 2014; McLean *et al*. 2014). Whole-farm models offer a cost-effective way of exploring farm management issues or revealing which research areas or management options require further study. Models can examine a range of scenarios by simulating how a farm system would perform under particular management options or environmental conditions, such as applying a range of stocking rates or herd structures, assessing the performance of pastures in particular climatic regions or soil types, or examining how a farm performs across years of low or extreme rainfall (e.g. O'Reagain *et al.* 2014). Farms are complex systems due to the numerous components that exist such as livestock, various pastures species or soil properties, and particularly, because of the interactions that take place between each of these components in response to climate. Whole-farm models enable the relationships that exist between farm components to be incorporated into one complete system that can be analysed over many years.

The Sustainable Grazing Systems (SGS) model is a biophysical, mechanistic model that includes modules for soil water and nutrient balance, pasture production and utilisation of multiple species, and animal intake and growth (Johnson *et al.* 2003). In SGS, animal intake is affected by available herbage, and grazing consequently influences herbage accumulation and growth (see Johnson *et al*. 2003). The SGS model uses a daily time-step and incorporates complex interactions between these modules. Most of the processes in SGS are determined by climate, particularly rainfall, temperature, solar radiation and vapour pressure deficit (or humidity). Farm performance is influenced by various selected farm management options such as the stocking rate regime, pasture species, fertiliser regime or irrigation schedule. Additionally, SGS is able to predict the greenhouse gas emissions (CH_4 and N_2O) from the farm as well as soil carbon fluxes (Johnson *et al*. 2008).

As a mechanistic model, SGS differs from the existing empirical model, GRASP, that has been used extensively for tropical rangeland systems in northern Australia (Scanlan *et al*. 2013). Empirical models use experimental data to describe what is occurring and to form single level relationships but these relationships may not be based on underlying biological processes (France and Kebreab 2008). Mechanistic models seek to understand underlying processes and examine the structure of the system, dividing it into modules and then analysing the performance of the whole system, as well as the connections between each of the modules (France and Kebreab 2008). SGS has been extensively used to model southern, temperate systems in numerous studies at various sites across southern Australia (see Graham *et al*. 2003; Lodge *et al*. 2003; Sanford *et al*. 2003; Cullen *et al*. 2008), but has yet to be tested for use in Australian tropical rangeland grazing systems. Models need to be evaluated to determine whether they perform acceptably for their anticipated purpose (Araújo and Guisan 2006). Although there has been debate over the term validation and the validation process when testing models (Oreskes *et al*. 1994), here the term validation is used to demonstrate whether the model is acceptable for its intended use (Rykiel 1996). This validation is performed by comparing simulated and observed data, a method of evaluation that is widely used (Clark *et al*. 2000; Bell *et al*. 2013; Pembleton *et al*. 2013; Scanlan *et al*. 2013). The aim of this paper is to validate the SGS model to determine if the model can produce a realistic simulation of a selected northern Australian beef system. The Wambiana grazing trial provides an opportunity to assess factors around beef business profitability, sustainability, net carbon position and validate a range of models (O'Reagain *et al*. 2011; Scanlan *et al*. 2013; Bray *et al*. 2014). Additionally, this paper identifies further developments in SGS to help improve how the model represents tropical Australian grazing systems by simulating the long-term grazing trial at Wambiana.

Methods

The Wambiana site

The Wambiana grazing experiment is a long-term research site (1997–2014) situated ~70 km south-west of Charters Towers, Queensland (20°34′S, 146°07′E) on a commercial beef property. Long-term (1905–2012) average annual rainfall for the site is 640 mm but is highly variable (range of 207–1409 mm) with rainfall largely summer-dominant (O'Reagain *et al*. 2011). There are three main soil types each associated with distinct types of savanna woodland: (1) moderately fertile brown sodosols and chromosols dominated by Reid River box (*Eucalyptus brownii*), (2) more fertile grey earths and vertosols dominated by brigalow (*Acacia harpophylla*) and (3) well drained, low fertility yellow/red kandosols dominated by silver-leaf ironbark (*E. melanophloia*) (O'Reagain *et al*. 2009). These three soil types will be referred to as the box, brigalow and ironbark soil types, respectively. The trial paddocks at Wambiana were fenced so that each paddock had roughly the same percentage of the three major soil types. Therefore, 55% of the paddock areas had the box soil type, 22% was brigalow and the remaining 23% of the paddock was ironbark (O'Reagain and Bushell 2011) and cattle were free to selectively graze on any of these soil types within each paddock.

The site was dominated by native C_4 grasses with all soils having some 3P species (defined as perennial, productive and palatable grasses). The box soil type was dominated by 3P (*Chrysopogon fallax* and *Bothriochloa ewartiana*), as was the brigalow soil (*Dichanthium sericeum* and *Bothriochloa ewartiana*) and the ironbark soil mainly had unpalatable grasses (*Eriachne mucronata* and *Aristida* spp.) yet also contained around 30% of 3P grasses *Chrysopogon fallax* and *Heteropogon contortus* (O'Reagain *et al*. 2009). Pasture data were measured annually from 1998 to 2012 using the BOTANAL procedure (Tothill *et al*. 1992) at the end of the wet season (May), which was close to the annual peak of pasture mass.

Five different stocking strategies were applied at the Wambiana trial with two of these, the moderate stocking rate (MSR) and heavy stocking rate (HSR), used in this modelling study and in the companion study assessment of the net carbon position at Wambiana (Bray *et al*. 2014). The MSR had 8–10 ha/animal equivalent (where 1 AE = a 450-kg steer; McLean and Blakeley 2014) and the HSR had 4–5 ha/AE (O'Reagain *et al*. 2009). Steers with similar genetics were purchased every year in June from James Cook University research station 100 km north of the trial, or from a property ~120 km west of Charters Towers (O'Reagain *et al*. 2009). Prior to 2001 steers were sold after 1 year but from 2001 onwards, steers were kept for 2 years with a new group still purchased each year. The average animal starting weight from 2001 was 239–391 kg and before 2001 the average starting weight was 239–305 kg. Steers were weighed on entry to the Wambiana site and every 6 months thereafter until the steers were sold 2 years later in June. Steers were destocked for 3 months in 2004 from one of the HSR paddocks as a result of drought. Urea lick blocks were supplied to both treatments in the Dry season in 2003 with urea subsequently supplied as dry loose-mix in tubs until 2012. Further details of the Wambiana long-term experiment are detailed in O'Reagain *et al*. (2011).

Model simulations

The area modelled was scaled up to 1000 ha to avoid errors in rounding animal numbers, which may have occurred if the paddocks were kept at their original size of ~100 ha. Each soil type was modelled as a separate simulation in SGS and the area for box, brigalow and ironbark therefore consisted of 550, 220 and 230 ha, respectively.

The MSR and HSR treatments were modelled at 8 ha/AE and 4 ha/AE, respectively, across the whole 1000-ha simulation. Previous research using GPS collars (Tomkins *et al*. 2009) had demonstrated that steers at the Wambiana site had a preference for grazing on brigalow soil, followed by the box soil and then the ironbark soil. To reflect this preference, the number of steers that could be sustained on each soil type was calculated using the fodder budgeting program Stocktake (FutureBeef 2014), which is a paddock-scale software program that uses land condition and grass growth predictions to calculate the carrying capacity of a particular soil type. Based on Stocktake the calculated carrying capacity for the box, brigalow and ironbark soils were 3.8, 2.8 and 7.9 ha/AE (or 58%, 31% and 11% of total stock), respectively, and were therefore the stocking rates used for each soil type in SGS. When the different land sizes for each soil type were taken into consideration, these three stocking rates equalled 4 ha/AE for the HSR treatment over the total 1000 ha. The MSR had half the number of stock of the HSR and therefore the stocking rates for the box, brigalow and ironbark soils were set in SGS at 7.6, 5.6 and 15.8 ha/AE (or 58%, 31% and 11% of total stock), respectively. A single starting weight was required in SGS and therefore, although there was variation in animal starting weights across the years, 330 kg was used, which was the average starting weight of steers from 2001 to 2012. Since each soil type was modelled separately in SGS, there were different liveweight figure outputs for each soil type. These liveweight figures then needed to be combined and the final steer liveweight was calculated by multiplying the liveweight of steers by the percentage of stock on the particular soil type and then adding the liveweights together.

The model was run from January 1988 to December 2012, with the first 10 years being discarded to allow the parameters in the model to settle. However, a longer period was required for the soil carbon to stabilise and therefore the 'loop' function was used in SGS for 10 rotations, which runs through the model 10 times, allowing soil carbon to stabilise over a longer period. SILO data drill daily climate data was used (see www.longpaddock.qld.gov.au/silo/, verified 1 March 2014) for the research site.

Pasture parameter sets for 3P grasses and tropical annual grasses

SGS simulates paddocks with multiple pasture species, but it is common for over a hundred pasture species to grow in the northern Australian rangelands at the paddock scale. Incorporating a vast number of species in SGS is impractical, and so pastures were modelled according to grouped species. Pasture parameter sets were developed in SGS for two new pasture groups: (1) 3P grasses that grow quickly in response to rain and are an important part of profitable tropical rangeland grazing systems, and (2) annual grasses that incorporate a range of grasses from tropical rangeland grazing systems. Grasses, forbs, sedges and native legumes usually consisted of <10% of total standing dry matter (TSDM) and were ignored. Unpalatable grasses (*Eriachne mucronata* and *Aristida* spp.) were also excluded from the simulation and measured TSDM data points.

SGS is a mechanistic model, thus all parameters have an underlying biophysical interpretation, and so the strategy for parameterising the plant species is to focus on the underlying physiology. For example, the rates of transfer of standing dead material to litter were taken to be 0.3% per day for the perennial pastures but the higher value of 1% per day was used for the annual grasses. Root depth for 3P and annual grasses were taken to be 100 cm and 60 cm, respectively (Murphy 2010). The percentage of new shoot growth allocated to leaf was defined as 45% for both 3P and annuals, which is considerably lower than is generally applied to temperate species, reflecting morphological differences. Likewise, specific leaf area at ambient CO_2 (m^2 leaf/kg dry weight) was 15, which is lower than what is usually seen in temperate species and the amount of N uptake was 1000 g N/t root dry weight/parts per million/day for NO_3 and NH_4 uptake. Additionally, the annual grasses were assumed to have a lower grazing preference, digestibility and leaf N than 3P grasses.

Analysing the data

The observed and modelled pasture data analysed were TSDM in t/ha, which included green and dry herbage but not litter, the amount of 3P grasses and annual grasses and steer liveweight (kg).

Several evaluation statistics based on Tedeschi (2006) were used to compare modelled and observed values for TSDM of pasture. The statistics calculated were measured mean; modelled mean; mean bias, being the difference between the measured and modelled mean; coefficient of determination (r^2) as a measure of precision; mean prediction error, which indicated the efficiency of the model as a percentage of the mean; model efficiency indicated the amount of variance between the measured and modelled output with 1 signifying a perfect fit; variance ratio was the level of variance in the observed and simulated values and a value of 1 showed the same level of variance; bias correction factor showed how far the regression line moved from the slope of y = × with a value of 1 meaning there is no bias; and the concordance correlation coefficient (Lin 1989) was a measure of both accuracy and precision with a value of 1 indicating a perfect fit. The number of observations for TSDM was 90 in total i.e. 2 × stocking rate treatments × 3 soil types × 15 years. The observed values were the average of measurements from each replication taken in May and modelled values were the average of a month's pasture before 1 May, to capture some of the variation that is expected around the measured point. The number of observations for steer liveweight was 94 and the coefficient of determination (r^2) and mean prediction error were also calculated for the observed and modelled liveweights.

Results

The measured and simulated outputs for TSDM for each dataset are presented in Fig. 1. The SGS model represented the year-to-year variation in pasture production well with a significant relationship ($n = 90$, $P < 0.001$) and a variation (r^2) of 0.60 between the modelled and observed TSDM. The modelled results for the HSR were mostly clustered towards the lower end due to reduced herbage mass from heavier grazing; however, there was greater variation between observed and modelled values in the TSDM results for HSR than the MSR treatment. The mean across all measured TSDM data was 1.68 t DM/ha, compared with a mean of 1.80 t DM/ha for all modelled outputs and the mean bias was therefore –0.12 t DM/ha. The mean prediction error was 47% and model efficiency, which ideally should be above 0.50, was 0.57. The variance between observed and modelled values was 1.09, indicating that there was greater variation in the measured data than in the simulated data. The bias correction factor was 0.99, indicating that there was only minor deviation from the 1 : 1 line and the concordance correlation coefficient had slightly greater variation at 0.76.

The contribution to yield of 3P and annual grasses are shown for each of the soil types in Fig. 2 and Fig. 3 for the MSR and

HSR treatments, respectively. Modelling species composition can be difficult due to competition effects and grazing characteristics, but SGS managed to represent the measured pattern of 3P and annual grass growth adequately. The modelled pasture growth reflected the reduced annual rainfall (July–June) in 2001–02 to 2005–06 of 350–518 mm, compared with an annual rainfall of 558–1196 mm for the other years. As expected, differences in productivity could also be observed across the various soil types. The brigalow soil was the most productive of the three soil types and despite having a relatively higher grazing pressure, produced roughly the same amount of TSDM as the box soil. In contrast, the ironbark soil, being both less fertile and sandier, retained less water than the other two soil types and hence produced less pasture. Additionally, the seasonal and year-to-year differences in liveweight gain are shown in Fig. 4 for both MSR and HSR stocking rate treatments. The variation in liveweight (r^2) was also 0.60 with a significant relationship ($n = 94$, $P < 0.001$) and a mean prediction error of 18.5%.

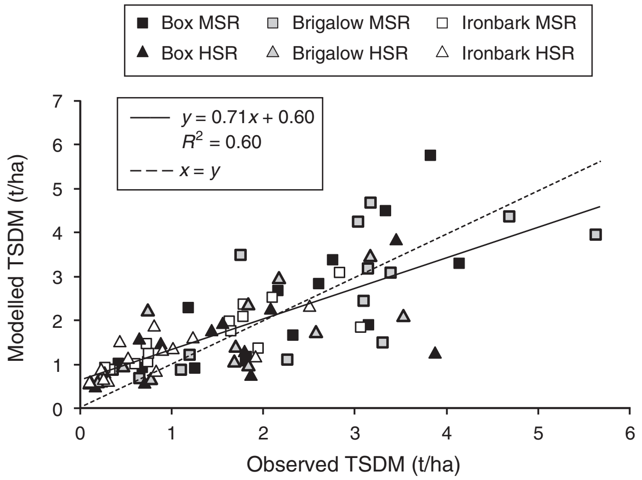
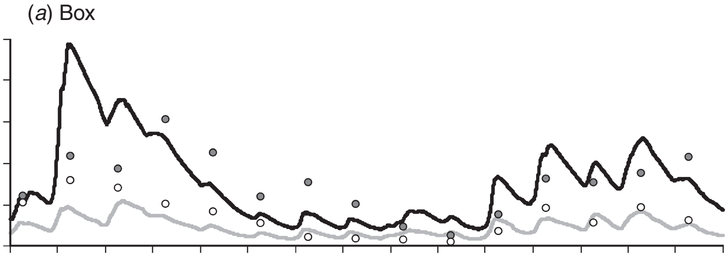
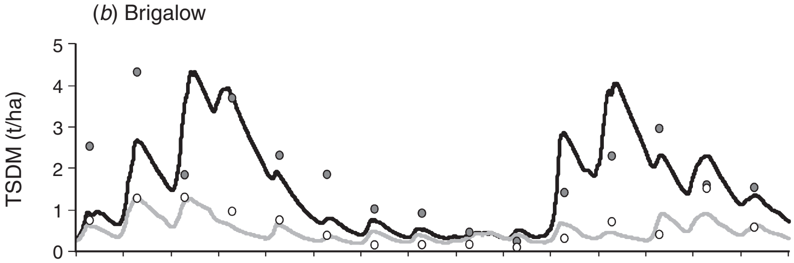


Fig. 1. Measured and simulated total standing dry matter (TSDM) for the moderate stocking rate (MSR) and heavy stocking rate (HSR) on box, brigalow and ironbark soil types.

Discussion

The results demonstrate that the SGS model can realistically represent pasture TSDM and the relative contribution to yield of 3P and annual grasses over both multiple soil types (Fig. 1) and different stocking rates (Figs 2 and 3). Additionally, the modelled animal liveweight and liveweight gain showed a good


(*a*) Box


(*b*) Brigalow

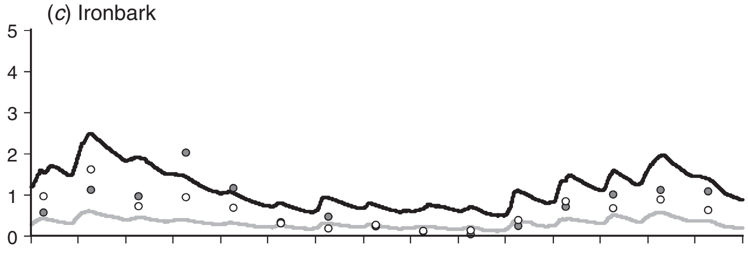

(*c*) Ironbark

Fig. 2. Measured (points) and simulated (lines) total standing dry matter (TSDM) of 3P (black lines and points) and annual grass (grey lines and points) species composition for (*a*) box, (*b*) brigalow and (*c*) ironbark soil types for the moderate stocking rate treatment.

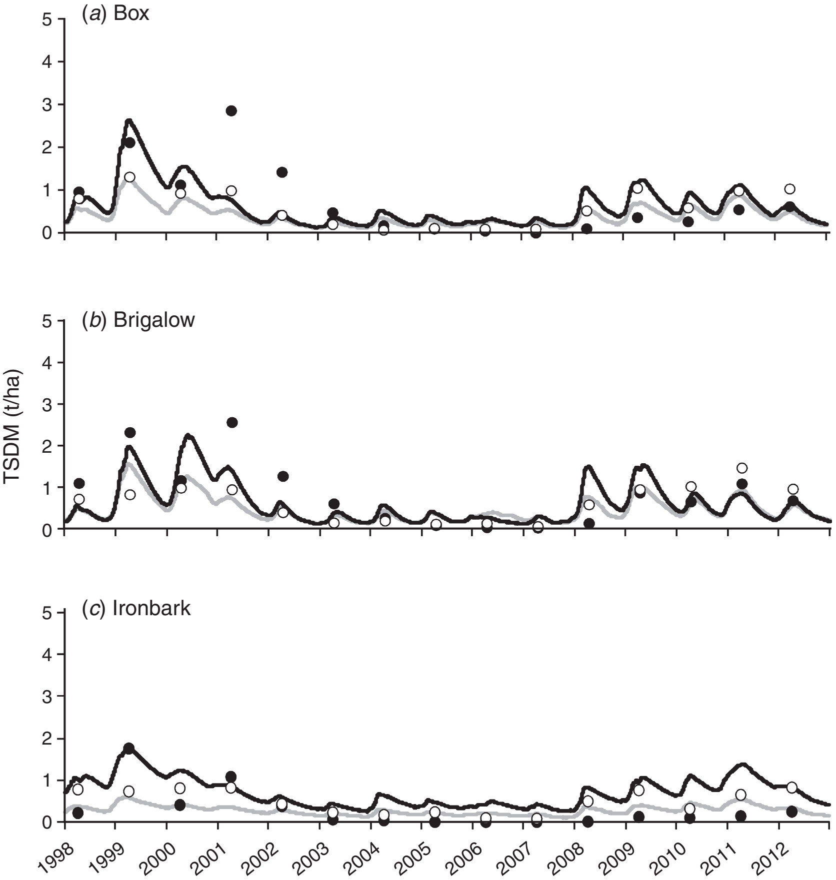


Fig. 3. Measured (points) and simulated (lines) standing dry matter (TSDM) of 3P (black lines and points) and annual grass (grey lines and points) species composition for (*a*) box, (*b*) brigalow and (*c*) ironbark soil types for the heavy stocking rate treatment.

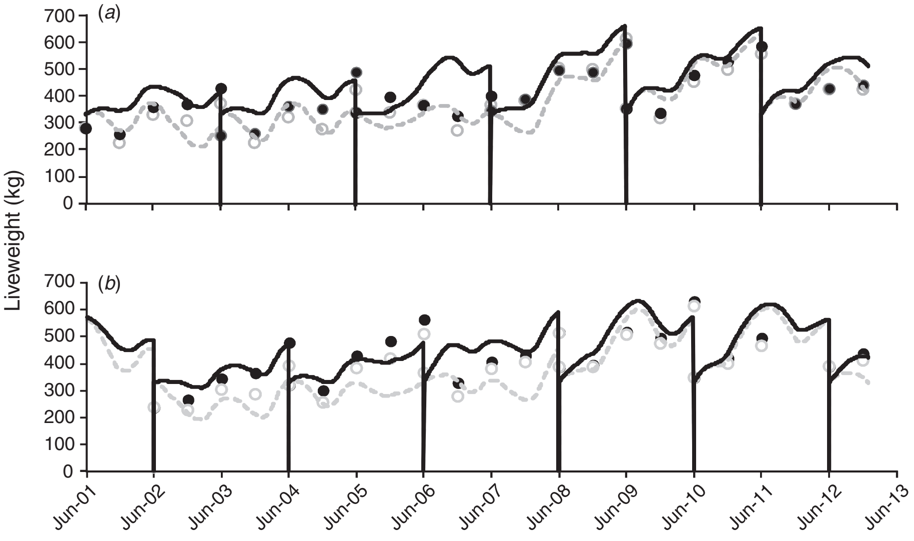


Fig. 4. Measured (points) and modelled (lines) steer liveweight with animals purchased in (*a*) odd numbered years and (*b*) even numbered years. Steers remained on the farm enterprise for 2 years for the moderate stocking rate (black lines and points) and the heavy stocking rate measured (grey lines and points).

representation ($r^2 = 0.60$) of the measured liveweight of steers at the Wambiana site (Fig. 4). TSDM across the whole dataset produced a mean bias of –0.12 t/ha and although the mean prediction error at 47% was above what is usually considered to signify model accuracy (<20%) the results were similar to other studies using pasture and grazing models (Jouven *et al.* 2006; Robertson 2006; Cullen *et al.* 2008).

There are challenges with comparing observed and simulated TSDM data in grazing systems. Variation in the results can occur due to sampling and measurement error, limitations in the model, or a combination of both. The variation from measured data may also occur due to the difficulty in accurately measuring pasture mass (Cullen *et al.* 2008), particularly in large spatially variable paddocks and the uncertainties associated with comprehensively capturing all aspects of the growth conditions (White *et al.* 2008). There was a discrepancy between the measured and modelled data in the wet season of 2006–07 with modelled steers in the MSR paddock having greater liveweight gain than at the Wambiana site (Fig. 4*a*). During this time there was reduced pasture availability and a decline in pasture vigour due to the preceding dry years, yet this was the only point where the measured liveweight data had a different growth pattern to other years, which would have been influenced by changes in management (e.g. the introduction of urea feeding) at that time. There may also have been an inconsistency in the measured data, or it may point to the inability of the model to adequately represent changes in species composition, reduced plant vigour and changes in nutrient cycling that may occur under drought and subsequent drought recovery. There were some variations at the Wambiana site that could not be captured in the model, such as steers at the site being kept for only 1 year between 1998 and 2001, which may have influenced the amount of TSDM available during these years due to different patterns in liveweight gain and consequently rates of pasture intake.

Pasture TSDM can also vary markedly across paddocks due to spatial variability in rainfall, patch grazing (Hirata 2000) and underlying soil heterogeneity, even within soil types. This spatial variability has been studied by Pringle *et al.* (2011) who noted that soil organic carbon was influenced to a depth of 0.3 m in the soil due to the interaction between soil type and grazing pressure. Data from the Wambiana site was averaged across two replicate paddocks and there were instances where these differed in TSDM by up to 2 t DM/ha for the same stocking rate and soil type. This amount represents a large range of acceptable TSDM values in the paddock. Therefore, while the modelled output may have been within the range of observed values, at times the modelled outputs appeared less accurate when compared with the paddock average. There was additional variability as a result of modelling multiple species as a group, which in reality vary in forage quality and growth characteristics between species, particularly for the annual grasses. However, these annual grasses usually comprised a smaller amount of TSDM than the 3P grasses and therefore this additional variation would have had less of an effect on the overall simulation than differences when modelling multiple 3P grasses.

Modelling work has also been conducted for the Wambiana site by Scanlan *et al.* (2013) using the empirical model GRASP, which produced a close relationship between observed and modelled values for TSDM at the paddock level of $r^2 = 0.82$, compared with $r^2 = 0.60$ in this study. However, the GRASP study looked at the box soil type only, whereas the relationship in SGS was for the box, brigalow and ironbark soil types. Similar difficulties existed in both models for matching observed liveweight during 2004–05 and 2006–07, however these years were excluded from the GRASP analysis, producing a good relationship ($r^2 = 0.64$), which was similar in SGS ($r^2 = 0.60$). In general, empirical models, where parameters are fitted directly to observational data, tend to give closer agreement than mechanistic models (Thornley and Johnson 2000). However, while outputs from mechanistic models tend to be more variable than those from empirical models, mechanistic models provide greater insight and understanding of the underlying biophysical process and the relationships that exist, such as the interaction between soil properties, pasture growth and animal intake. Additionally, mechanistic models are less site-specific because they can be more easily applied to other sites than empirical models, which are tied to the database used to create it (France and Kebreab 2008). As SGS is a mechanistic model, all model parameters have an underlying biophysical interpretation. By defining species characteristics through the key parameter values defined in the methods, we have been able to demonstrate that the model simulations are in agreement with observed values.

For example Cullen *et al.* (2008), using the same set of physiological parameters for perennial ryegrass, demonstrated good agreement between the model and observations for a wide range of locations in Australia and New Zealand. As mentioned earlier, Oreskes *et al.* (1994) highlight possible limitations when comparing models with experimental data within complex natural systems. This is apparent in the present work where we were unable to incorporate all management strategies that were applied at the site in the model simulations. It is important, therefore, that we look for consistency in the simulated output as well as agreement with the data. For example, the lower simulated liveweights during 2006–07 are consistent with the lower pasture growth rates due to lack of rain and reflect the fact that, in the simulations, the stock were not removed from the paddock or fed supplements.

There are some further developments of the SGS model that would help improve the model predictions of TSDM and animal liveweight. First, while SGS has a comprehensive way of providing supplementary feeds which are more relevant to temperate grazing systems, there is currently no method for including urea supplementation in the model, which is commonly provided to animals in northern Australia to compensate for low forage protein in dry conditions. Urea supplementation was supplied at the Wambiana site to both treatments during the Dry seasons (May–November) of 2003–04 to 2011–12 and contributed to higher measured liveweights of steers during these years, which can be seen in Fig. 4*b*.

Another useful addition to the SGS model would be a management option to destock during severe drought. In 2004 one of the HSR paddocks at Wambiana was destocked for 4 months due to lack of feed (O'Reagain *et al.* 2009). Molasses and urea drought feeding was also provided to the

HSR steers at the Wambiana site for short periods in the Dry season from 2003–04 to 2006–07. The modelled outputs for the HSR (Fig. 4) showed lower liveweights than measured at certain points during 2004 and 2005, which probably reflects these factors.

The ability for pastures to recover following extended periods of drought and heavy grazing as happened in the HSR should be further refined in the SGS model. The modelled pasture recovered more quickly after the drought years than data from the Wambiana site would suggest (see Fig. 2*a* from 2006 onwards) because the model does not include cumulative effects of consecutive droughts and overgrazing on species survival and consequent growth. While SGS suppressed growth with reduced rainfall, it did not kill the plants and was consequently able to recover more quickly with the return of rain after drought seasons.

The inclusion of a tree component that incorporated tree basal area would assist in the model's representation of tropical rangeland systems. Many Australian tropical rangelands have trees of different sizes that compete with pastures for water and light and this interaction becomes an important consideration for farm management decisions. Northern Australian systems also include fire, which may be used to remove dead forage and/or manage tree density. Although SGS does include fire, regrowth following fire appeared significantly slower than was observed and therefore the fire component was excluded from this study. This is an area that could be explored further.

The development of parameter sets for other pasture species groups such as unpalatable grasses, forbs, other 2P grasses (that are any two of the following: perennial, productive or palatable), native legumes and invading exotic grasses would be useful. Although these other pasture species comprise a relatively small component of total TSDM at the Wambiana site, the availability of additional pasture parameter sets would increase the model's ability to answer important issues facing rangeland managers in northern Australia.

Conclusion

We have explored the potential for applying the SGS model to northern Australian beef grazing systems. The analyses presented here demonstrate that the SGS model is able to simulate pasture TSDM and steer liveweight gain in a northern Australian beef system. The model predictions of 3P and annual grasses were reasonable (r^2 = 0.60) when compared with observed values over a range of soil types and stocking rates, providing preliminary evidence that the SGS model could be used to simulate these rangeland systems. However, this research would benefit from further testing to verify that the new pasture parameters of 3P and annual grasses are suitable at other sites across Queensland and the Northern Territory, particularly documenting essential changes to these parameters used in this case study.

Empirical models cannot be used beyond the site of the data that was used to create them without changing the fundamental relationships used in the model. Mechanistic models rely on processes and are valuable once validated in that they can more easily be applied across a variety of rangeland conditions with some predictive ability. While the SGS model would benefit from further validation for tropical rangeland systems, the model is more versatile than an empirical model because it can be transferred more easily to different sites.

There are several recommendations for further model development including the incorporation of urea supplementation for use in the Dry season, the ability to destock during drought, accounting for the effect of trees and tree size into the model, the use of prescribed burning and the development of pasture parameter sets for other species groups such as unpalatable grasses and forbs.

The SGS model has been widely used in temperate and subtropical grazing systems in southern Australia. This paper for the first time provides some evidence that this utility could be extended to tropical rangeland systems, particularly to allow the research from the Wambiana long-term grazing site to be extended to other locations. There is considerable potential to extend the present analysis to other tropical rangeland grazing regions in Australian. The model gives an integrated, balanced treatment of plants, animals, soil water, soil organic matter, nutrient dynamics and greenhouse gas emissions. Given the mechanistic nature of the model, it has potential to be applied in a range of studies, such as risk assessment of management strategies, climate change mitigation, and supplementary feeding regimes.

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