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Summer-growing perennial grasses are a potential new feed source in the low rainfall environment of southern Australia

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Abstract. In the Mallee region of southern Australia, the dry and variable climate results in frequent summer–autumn feed gaps, restricting the profitability of farms that combine livestock and crop enterprises. To assess the suitability of summer-growing perennial grasses to fill such feed gaps, two replicated field experiments comparing the persistence and productivity of several cultivars were conducted at Hopetoun and Karoonda. The data from these experiments also served to validate a C4 grass model, which was then used in a simulation experiment comparing productivity on two different soil types at three locations. Most grass cultivars established well except on sandy, non-wetting soils. At Hopetoun, four of five cultivars persisted over 6 years, demonstrating the tolerance of the selected cultivars to the typical long, dry summers and cold, wet winters of the region. Biomass production showed little difference between cultivars and a strong response to the amount of summer rainfall, ranging from 1500 to 3000 kg ha^{-1} under average seasonal conditions and peaking at 9000 kg ha^{-1} in the very wet summer of 2010–2011. Model performance was satisfactory (R^2 0.85–0.93, RMSE 476–1673 kg ha^{-1}, depending on the cultivar), in terms of predicting both the magnitude and the timing of biomass production. Simulation outputs indicated that biomass production closely followed seasonal trends in temperature and moisture availability. Grazing potential was highest from early summer to autumn, which coincides with the period of feed shortages and highest marginal value of forage. In areas with warm-season (October–April) rainfall averages of 175 and 225 mm, the grazing of C4 grass pastures on marginal soils would be possible in at least 40% of the years for 2 and 3 months, respectively. It was concluded that summer-growing perennials are a promising option to alleviate feed gaps on mixed crop–livestock farms in areas with at least 150 mm of rainfall from October to April.

Additional keywords: cereal–sheep systems, GRAZPLAN model, on-farm trials, panic grass, Rhodes grass.

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Introduction

The Mallee agro-ecological zone in south-eastern Australia is a low-rainfall environment (annual rainfall 250–350 mm), characterised by hot, dry summers and cool, moist winters. In the dryland farming systems where wheat and barley are combined with sheep production, regular feed gaps over summer and autumn (Moore *et al*. 2009) are commonly met by feed supplementation. The reliance on supplementary feeding limits farm profitability (Robertson 2006*a*) and explains low stocking rates and, therefore, low pasture utilisation and resource-use efficiency. With the revitalisation of the grazing component of mixed farming systems due to increasing wool and lamb prices (Bell and Moore 2012), strategies to close the feed gap by differentiating the feed-base are receiving renewed attention (Nichols *et al*. 2007; Dear and Ewing 2008). Perennial forage sources that provide high-quality feed during the dry season hold particular promise in this regard, especially in regions with a hot and dry summer such as the Mallee. In these environments, warm-season plants grow out of phase with the majority of the other rainfed feed resources growing in winter and spring, and, as such, make use of water and nutrients otherwise not productively utilised (e.g. Johnston *et al*. 2005). Therefore, the inclusion of summer-growing perennials in the feed-base provides green forage for livestock during the dry summer–autumn season when common annual pasture species are not productive (Madakadze *et al*. 1998).

Besides alleviating feed gaps, summer-growing perennials have potential to reduce high erosion risk in summer–autumn, increase the production from marginal cropping soils, and assist with controlling weeds (Moore *et al*. 2006; Harris *et al*. 2007; Millar and Badgery 2009; Byrne *et al*. 2010; Finlayson *et al*. 2012). Furthermore, including perennials in the farm feed-base is reported to increase biodiversity both above- and belowground (Collard and Fisher 2010; Glover *et al*. 2010). With the development of future farming systems in mind, summer-growing grasses can also be used as a basis for pasture cropping by inter-sowing winter crops, a practice that is gaining popularity throughout the southern Australian cropping zone (Millar and Badgery 2009; Finlayson *et al*. 2012; Thomas *et al*. 2014, this issue). In areas wetter than the study region, another advantage of perennials relates to their deep root system, leading to reduced deep drainage and a lower risk of rising watertables, salinity, acidity and nitrate leaching (e.g. Dear *et al*. 2008; Boschma *et al*. 2009). The disadvantages of including perennial pasture species in the feed-base are associated with financial risks of poor establishment and the difficulty of removing them when returning to cropping (Finlayson *et al*. 2012).

Most of the available varieties of perennial, summer-growing, subtropical, or C4 grasses are native to subtropical regions of southern and central Africa or South America. They have been used in Australian livestock production systems for a long time in the subtropical regions of the country (see e.g. Milford and Minson 1968; McCosker and Teitzel 1975; Lloyd 1981; Lloyd *et al*. 1991). In the temperate climates of Australia, subtropical grasses are common in areas with wet summers and/or relatively high rainfall (McCormick *et al*. 1998; Johnston *et al*. 2005; Boschma *et al*. 2008, 2009; Nie *et al*. 2008; Reed *et al*. 2008; Whitbread *et al*. 2009). First evidence that summer-growing grasses can grow and persist in dry summer climates in Australia came from Western Australia (WA) (Moore *et al.* 2006), where >50 000 ha has been established on the more marginal sandy soils of the medium–low rainfall zone (G. Moore, pers. comm.). Permanent pastures of subtropical grasses are successfully grown there thanks to their ability to persist through dry periods and because of their cold tolerance (Moore *et al*. 2006). In the northern agricultural region of WA, the perennial grasses perform well because they continue growing actively during winter, with a reduction in growth only during July–August. Other temperate regions where subtropical species are used include summer-dry Italy (Gherbin *et al*. 2007; Corleto *et al*. 2009) and summer-wet United States (Corson *et al*. 2007) and Canada (Madakadze *et al*. 1998).

Soil and climate differences between the Mallee and Mediterranean-type climate regions where subtropical grasses perform well prevent a simple transfer of those results. Experimental evidence to confirm the potential of these grasses in the Mallee is still lacking. This study therefore reports on the first on-farm trials with several grass species in the Mallee. Critical environmental constraints for the survival and persistence of perennials include prolonged dry periods and high and low temperatures (Nie *et al*. 2008), which occur commonly in the Mallee climate. A multi-year trial was therefore necessary to investigate performance over time.

Grassland simulation models can usefully complement experimental studies to assess the long-term biomass production and grazing potential of forages over a range of soils and climates (Clark *et al*. 2003; Bryant and Snow 2008), thereby allowing the exploration of options to extend and diversify the feed-base and the design of future sustainable farming systems (Finlayson *et al*. 2012). Several modelling studies of C4 perennial grass pastures have been carried out in the tropics (e.g. Lara *et al*. 2012; Araujo *et al*. 2013) and in temperate regions (Stout 1994; Corson *et al*. 2007; Di Vittorio *et al*. 2010). However, the only modelling analysis of C4 perennial grasses in a winter-dominant, low-rainfall environment is a study in WA (Lawes and Robertson 2008). In that study, the APSIM plant growth model was used to represent the growth of Rhodes grass (*Chloris gayana* Kunth). The main finding was that in Mediterranean climates, adding Rhodes grass to the feed-base had potential to extend the existing growing season into late spring and early summer. Although the APSIM model was calibrated to experimental data by Lawes and Robertson (2008), no results of model testing were presented. APSIM has been extensively used mainly in cropping systems, but a few other examples of its use in grazing systems exist (e.g. Verburg *et al.* 2007; Bell *et al.* 2008; Li *et al.* 2011).

The GRAZPLAN grassland simulation model (Moore *et al*. 1997) has been used previously in studies of species that make up the bulk of the feed-base in the Mallee region (Robertson 2006*b*; Moore and Ghahramani 2013), and it can also be used in conjunction with the APSIM soil and crop models to analyse the mixed farming systems within which most pastures in the Mallee are grown (e.g. Moore 2009). Although the GRAZPLAN model has been applied to model a range of different Australian pasture types (Donnelly *et al*. 2002), its perennial C4 grass module has not yet been tested with experimental data from low-rainfall regions. For perennial forage species, the main differences between the GRAZPLAN and APSIM-Plant models are that the former explicitly models gross photosynthesis and respiration, it includes a submodel for remobilisation of belowground reserves, and it follows the nutritive value dynamics of leaves and stems, providing a firm link to a ruminant dynamics model.

The aim of this study was to assess the contribution of perennial summer-growing grasses to diversify the feed-base and reduce feed gaps over summer and autumn in the Mallee region of southern Australia. To this end, we (*i*) assess the multi-year trial performance of summer-growing perennial grasses in the Mallee region; (*ii*) evaluate the accuracy of the GRAZPLAN model in simulating biomass production of perennial C4 grass cultivars in a low-rainfall environment; and (*iii*) explore the timing of feed production and the grazing potential of perennial summer-growing grasses under typical climate and soil conditions of the Mallee.

Methodology

Trials

A replicated on-farm trial was established in November 2006 at Hopetoun, Victoria (35°43′S, 142°16′E), on a sandy loam with clay at depth (0.4 m) and moderate subsoil constraints (electrical conductivity >0.5 dS m^{-1} at 50 cm) (Table 1). Preliminary results are presented by Whitbread and Craig (2010). A second trial was sown in October 2010 at Karoonda, South Australia (35°05′S, 140°06′E), on a sandy clay loam with a coarse sandy topsoil (Table 1). Both soils are classified as Calcarosols (Isbell 2002). Hopetoun and Karoonda have similar average annual rainfall of ~340 mm, with average warm-season rainfall (October–April) of 176 and 158 mm, respectively. At Hopetoun, the first three

Table 1. Initial soil characteristics for the trial sites at Hopetoun and Karoonda

Depth (mm)	pH (H_2O)	Org. C (g/kg)	NO_3-N	NH_4-N (mg kg^{-1})	Colwell P	Electrical conductivity (dS m^{-1})	Boron (mg kg^{-1})	Texture class
					Hopetoun			
0–100	7.3	13.2	3.0	6.0	31.0	0.1	1.1	Sandy loam
100–400	8.7	5.9	6.0	10.0	3.0	0.2	2.9	Sandy loam
400–700	9.2	6.4	4.0	13.0	4.0	0.3	7.9	Sandy clay loam
700–1000	9.5	2.9	4.0	7.0	8.0	0.3	13.4	Sandy clay loam
					Karoonda			
0–100	6.8	9.0	8.1	3.7	21.6	0.0	0.5	Sand
100–200	6.8	5.8	2.9	2.0	16.1	0.0	0.4	Sand
200–400	8.5	3.4	1.9	1.9	9.7	0.2	2.3	Sandy loam
400–60	8.9	2.8	2.2	1.7	5.0	0.4	7.9	Sandy clay loam
600–800	8.7	1.8	1.9	0.7	8.4	0.4	9.8	Sandy clay loam
800–1000	8.9	1.1	1.8	0.6	6.7	0.5	9.9	Sandy clay loam

Table 2. Grass cultivars used in the trials at Hopetoun and Karoonda with the average and range (in parentheses) of plant numbers (plants m^{-2}) at the end of the first summer after sowing

Hopetoun	March 2007	Karoonda	April 2011
Megathyrsus maximus (Jacq.) cv. Petrie panic	37 (14–86)	*Megathyrsus maximus* Jacq. cv. Petrie panic	5 (2–9)
Panicum coloratum L. cv. Bambatsi panic	34 (15–66)	*Panicum coloratum* L. cv. Bambatsi panic	3 (0–7)
Megathyrsus maximus Jacq. cv. Gatton panic	30 (10–45)	*Chloris gayana* Kunth cv. Katambora Rhodes grass	26 (18–34)
Panicum coloratum L. cv. ATF-714	35 (14–53)	*Digitaria eriantha* Steud. cv. Premier digit grass	3 (0.3–5)
Digitaria milanjiana (Rendle) Stapf cv. Strickland finger grass	41 (18–60)	*Setaria incrassata* (Hochst.) Hack. cv. Inverell purple pigeon grass	Failed to establish
Bothriochloa bladhii (Retz.) S.T. Blake subsp. *glabra* (Roxb.) B.K. Simon cv. Swann	Failed to establish		

seasons of the trial (2006–07, 2007–08, 2008–09) were dry, with lower rainfall than in 65% of cases in the last century. October–April rainfall totals in 2009–10 and 2011–12 were higher than average (~70% of last century's warm seasons were drier), and October–April rainfall in 2010–11 was the highest on record. Also at Karoonda, the first season of the trial (2010–11) was the wettest on record, and the second season was wetter than usual, with higher rainfall than in ~70% of the cases in the last century.

Species and cultivar selection (Table 2) was based on results from WA (Moore *et al.* 2006) and a species audit (Pengelly *et al.* 2006). Plot size was 25 by 3 m at Hopetoun and 25 by 4 m at Karoonda, with four replicates per cultivar at each site. At sowing, a knockdown herbicide and basal fertiliser were applied: 6 kg N ha^{-1} (Granulock Supreme Z) at Hopetoun and 9 kg N ha^{-1} (DAP) at Karoonda. Sowing was done with a conventional seeder at 17.5 cm row spacing at Hopetoun and 50 cm row spacing at Karoonda. At Hopetoun, two sowing rates (3 and 6 kg ha^{-1}) were compared, and at Karoonda one sowing rate of 5 kg ha^{-1} was used. At Hopetoun, the trial received 25 kg ha^{-1} of N (urea) in September 2009 and January 2011. Grasses were mown every year in May–June, and during summer, weeds were controlled where and when necessary. During the winter months, volunteer pasture growth was not controlled, but the plots were slashed to ~5 cm height with a mower towards the end of winter.

Regular measurements of pasture biomass and plant densities were performed every 1–2 months over summer–autumn from the establishment of each trial until April 2012. Shoot biomass was cut and removed from two or three randomly placed 1.0-m^2 quadrats per plot. Plant densities were recorded by counting plants in randomly placed row quadrats (six of 0.5 m length at Hopetoun, 12 of 1 m length at Karoonda). For Rhodes grass, with its spreading growth pattern, the number of plants was counted in four quadrats of 1 m^2 per plot.

Model description

The GRAZPLAN simulation model (Moore *et al*. 1997) is a biomass-based, multi-species model that operates at a daily time-step. Most of its development has focused on environments where variable water supply is a major factor limiting pasture productivity (Donnelly *et al*. 1998; Cohen *et al*. 2003). The model includes equations for the phenological cycles of various classes of perennial and annual plants; capture of light, water and soil nutrients; assimilation and respiration; the allocation of net assimilate between production of leaves, stems, roots and seeds; the dynamics of forage nutritive value; the death, fall, decomposition and disappearance of dead biomass; and the dynamics of the pasture seed bank. The model has been applied in Australia, including the Mallee region, to study questions about pasture systems, feed resources, tradeoffs with other farm activities (e.g. Robertson 2006*b*; Moore 2009; Moore and Ghahramani 2013) and in decision support for producers (Donnelly *et al*. 2002). In this study, the version of the grassland model corresponding to version 1.4 of the AusFarm software has been used in conjunction with the APSIM soil water and soil nutrient cycling models (Holzworth *et al*. 2014).

Model validation and simulation of grazing potential

The shoot biomass data for the four panic cultivars grown at Hopetoun were used to validate the GRAZPLAN model of a generic C4 grass (see Supplementary Material table 1 for a list of the parameters). Parameters were not changed for the specific cultivars. The model was run from 1 November 2006 to 10 May 2012 using SILO climate data for Hopetoun (www.longpaddock.qld.gov.au/silo) and initial soil nutrient content as derived from soil analysis (Table 1). Field measurements of drained upper limit, crop lower limit and rooting depth allowed determination of the plant-available water capacity. Initial soil water content was set to reflect conditions after the growth of a crop or pasture over winter with the water content in the upper layers (0–40 cm) at crop lower limit, in the lower layers (70–130 cm) at field capacity, and interpolated values for the layers in between. Pasture management operations such as sowing, mowing and fertiliser application were replicated in the simulations. Pasture growth during winter was ignored. Model performance statistics (Legates and McCabe 1999) such as the root-mean square error (RMSE), Nash–Sutcliffe model efficiency (EF) and the coefficient of determination (R^2) were calculated for each cultivar and for the average biomass of the four cultivars.

After validation, a simulation experiment was run using 60 years (1951–2010) of climate data for three locations (Fig. 1), for which both a high-potential soil and a low-potential soil typical for the Mallee were assumed. Sixty years of data were used to represent typical climate variability. In each of these long-term simulations, monoculture stands of the C4 grass were modelled with an annual application of 20 kg N ha^{-1} as ammonia on 1 October. Biomass was harvested and removed each year on 1 August, corresponding with the re-set of the soil organic matter module to avoid build-up or decline of soil fertility over time. The locations were chosen to include the range of rainfall conditions that can be expected in dryland southern Australia, going from a very dry climate in Waikerie (annual rainfall 258 mm, October–April rainfall 148 mm) to a wetter situation in Charlton (annual rainfall 403 mm, October–April rainfall 225 mm). The soil characteristics used in the simulation were based on actual measurements, conducted in this study for the high-potential soil, and in Whitbread *et al.* (2008) for the low-potential soil. The major differences between the high- and low-potential soils include rooting depth (1.3 and 0.6 m, respectively), plant-available water capacity (140 and 63 mm, respectively) and soil fertility, which is reflected in the soil organic carbon content (50.5 and 26.4 t ha^{-1} in the first 30 cm, respectively).

Simulation outputs were analysed to understand the temporal pasture growth rate pattern, and to assess monthly and annual biomass production across sites. Furthermore, in order to assess whether the pasture biomass availability could result in grazing at the right time to fill the feed gaps, the grazing potential was assessed using two different thresholds of minimum green biomass, 500 kg ha^{-1} (heavy grazing) and 1000 kg ha^{-1} (light grazing), and a minimum shoot dry matter digestibility threshold of 45%. The minimum dry matter digestibility was determined by conducting a small simulation experiment in which one dry sheep equivalent was allowed to graze a summer-growing perennial grass pasture of 1000 ha. The minimum digestibility at which the animal was able to increase its weight or maintain it >60 kg was ~45%, which corresponded with an effective diet digestibility of $\geq$55% (up to almost 75%) (data not shown). For each week of the year, the predicted green biomass and dry matter digestibility of the pasture allowed determination of whether the minimum thresholds were achieved. If that was the case, that week was earmarked as a week with potential grazing. The potential grazing probability of a week was defined as the percentage of years with potential grazing in that week. Potential grazing days per year were calculated by multiplying the number of weeks with potential grazing by seven.

Results

Trial results

At Hopetoun, establishment of the grasses was successful with the exception of *Bothriochloa bladhii*, and plant density of the successful species ranged from 30 to 41 plants m^{-2} at 1 year after sowing (Table 2). Sowing rate (3 or 6 kg ha^{-1}) had no effect on plant numbers or pasture biomass production. Pasture establishment at Karoonda was more variable, because of the non-wetting nature of the surface soil, and *Setaria incrassata* failed to establish (Table 2). At Hopetoun, plant numbers decreased in the second and third year of the experiment, but then stabilised at between 4 plants m^{-2} (Petrie) and 10 plants m^{-2} (ATF-714) from 2010 onwards. In the second year at Karoonda, plant density did not decrease and was between 4 plants m^{-2}

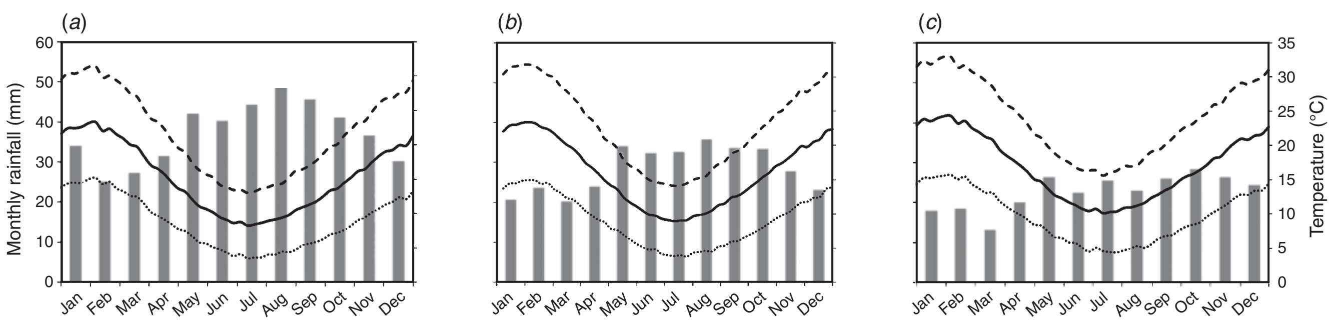

Fig. 1. Long-term average monthly rainfall and temperature at (*a*) Charlton, (*b*) Hopetoun and (*c*) Waikerie. Average daily maximum (– – –), mean (—) and minimum (. . .).

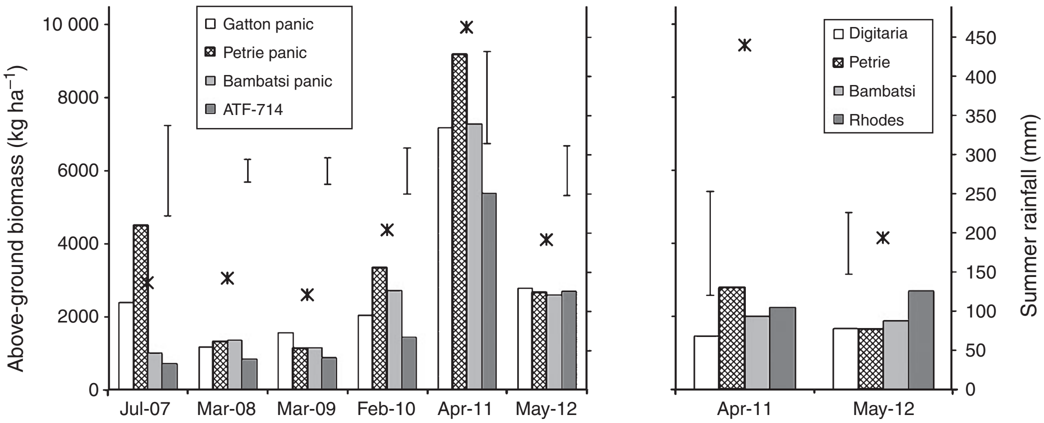

Fig. 2. Average peak biomass (bars) at Hopetoun (left) and Karoonda (right) with preceding warm-season (October–April) rainfall (*). Error bars indicate the least-squares difference between cultivars per year.

Table 3. Model performance statistics for the four cultivars separately and the average for four cultivars (last column) grown at Hopetoun from 2007 to 2012

R^2, Coefficient of determination; RMSE, root mean square error (kg ha^{-1}); EF, Nash–Sutcliffe model efficiency

Statistic	Gatton panic	Petrie panic	Bambatsi panic	ATF-714	All cultivars
R^2	0.91	0.85	0.91	0.93	0.93
RMSE	776	1673	880	476	753
EF	0.84	0.61	0.81	0.89	0.85

(Premier) and 25 plants m^{-2} (Katambora Rhodes grass). Further details on plant establishment and persistence at Hopetoun are reported in Whitbread and Craig (2010).

Biomass production at Hopetoun was strongly related to seasonal rainfall. Peak biomass was relatively low, ranging from 0.9 to 1.5 t ha^{-1} if October–April rainfall was <150 mm (first 3 years of the trial) but with October–April rainfall ~200 mm, pasture production ranged from 1.5 to 3.0 t ha^{-1} (in 2010 and 2012) (Fig. 2). In the wet summer of 2010–2011, with 463 mm of rainfall from October to April, biomass production peaked at 5.4–9.2 t ha^{-1} (Fig. 2). Relatively small differences in peak biomass production between cultivars were observed (Fig. 2). Only ATF-714 produced significantly less than one or two other cultivars in 3 of 6 years. Unlike Hopetoun, peak biomass production at Karoonda did not reach high levels in the wet summer of 2010–11 (Fig. 2). The grasses were only sown a few months earlier, and in some places establishment was poor. Peak biomass at Karoonda was not significantly different between cultivars, and similar to Hopetoun, at 1.5–2.8 t ha^{-1}. In addition, Rhodes grass, with its distinct stoloniferous growth pattern, had aboveground biomass production similar to the other grasses.

Model validation

The model predicted biomass production of the four cultivars well, with model accuracy highest for ATF-714 (Table 3, Figs 3, 4). For the other cultivars, model accuracy was acceptable most of the time, apart from the underestimation of the 2011 biomass production peak following the very wet 2010–2011 season (Fig. 4). In general, both timing and magnitude of biomass production were predicted in a satisfactory way by the model. Whereas biomass in early July 2007 was not well predicted for individual cultivars, the model prediction was close to the average of the four cultivars (Figs 3, 4). The model tended to over-predict biomass more than under-predict (Fig. 4). For all cultivars except Petrie, >50% of the model predictions were within a ±35% range of the observed value, and ~75% of model predictions were within that range for Gatton and for the average of the four cultivars.

Pasture growth and grazing potential across sites and soils

GRAZPLAN simulations based on 60 years of climate data indicate that biomass production closely follows seasonal trends in temperature and moisture availability (Figs 1, 5, 6). Pasture growth rates are high in spring and autumn when temperature is high and soil moisture is usually adequate. In summer, growth is often limited by moisture stress, whereas in winter, growth is limited by low temperatures (Figs 1 and 5). Seasonal dynamics in pasture growth rates result in the build-up of pasture biomass, reaching a maximum in February–March (Fig. 6). On the low-potential soil, differences in peak green biomass between sites are minor, with 1.2, 0.9 and 0.6 t ha^{-1} at Charlton, Hopetoun and Waikerie, respectively. Stronger differences between sites are observed on the high-potential soil, with mean peak live biomass amounting to 2.0, 1.5 and 1.0 t ha^{-1} at Charlton, Hopetoun and Waikerie, respectively. Across the three sites and the two soils, live biomass is negligible from July to October and very low in June and November.

The probability that a summer-growing perennial grass pasture can be grazed starts to rise in November and declines again rapidly in May (Fig. 7). Clear differences in potential grazing probability between locations relate to rainfall amount and pattern, whereas moisture availability and inherent soil fertility explain the lower probabilities on the low-potential

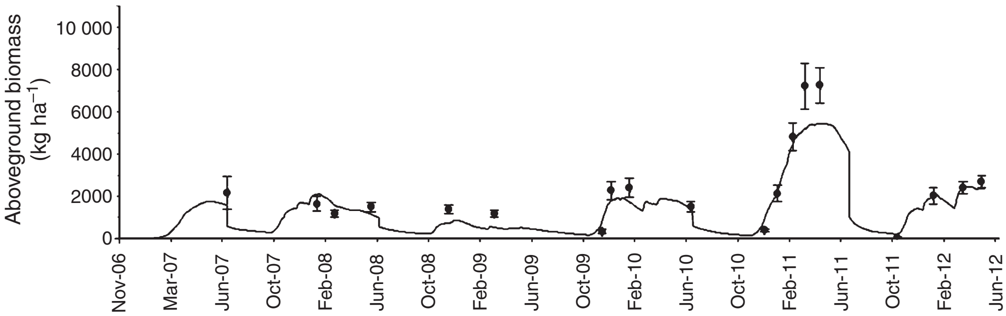

Fig. 3. Observed (●, with 95% confidence interval) and simulated (line) aboveground biomass at Hopetoun 2007–12. Observed values represent the average for all *Panicum* and *Megathyrsus* spp.

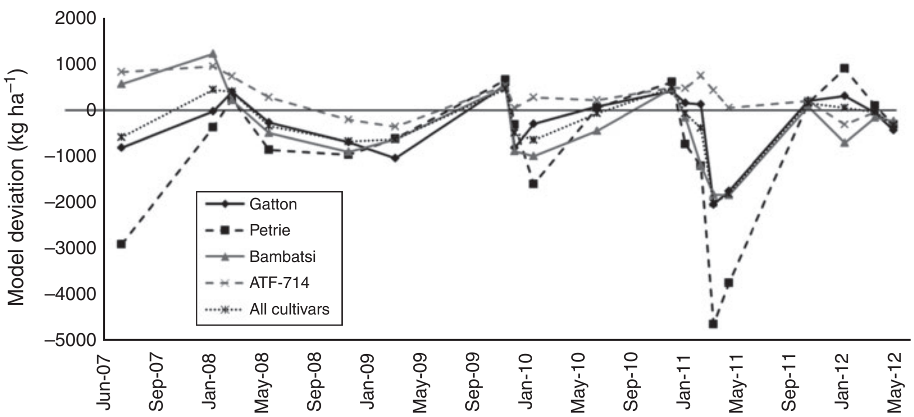

Fig. 4. Model deviations (predicted – observed) for aboveground biomass at Hopetoun 2007–12 for four *Panicum* and *Megathyrsus* spp. separately and the average for all cultivars.

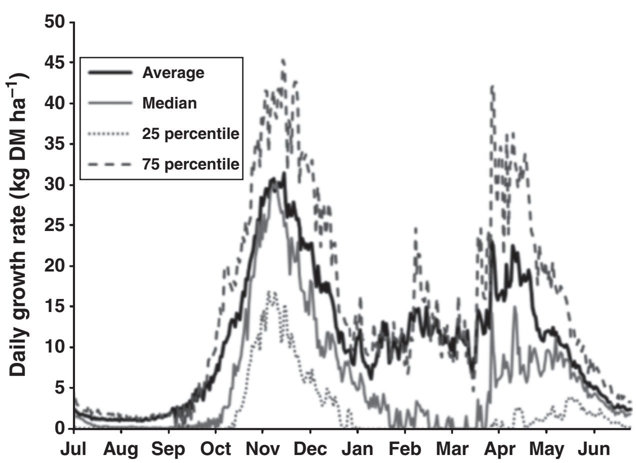

Fig. 5. Simulated daily growth rate for a summer-growing perennial pasture at Hopetoun 1951–2010.

soil than on the high-potential soil. The green biomass threshold also influences the potential grazing probability and its temporal dynamics. Predicted grazing opportunities were limited only by the available biomass dropping below the threshold; the simulated pasture digestibility never caused potential grazing restrictions. On the low-potential soil, the grazing potential is approximately half of that on the high-potential soil in the case of light grazing with a green biomass threshold of 1000 kg ha^{-1}. The heavy grazing threshold of 500 kg ha^{-1} is exceeded much more often, resulting in potential grazing probabilities of >60% and >80% through to the end of March in Hopetoun and Charlton, respectively. On the high-potential soil, however, the influence of the biomass threshold is less pronounced; very high probabilities are observed at Charlton throughout summer–autumn, and generally, low probabilities are obtained at Waikerie, both largely irrespective of the threshold (Fig. 7). Only at Hopetoun did the green biomass threshold influence the grazing opportunities, resulting in a 60–70% (light grazing) or a 80–90% (heavy grazing) potential grazing probability until the end of March. On the low-potential soil, the average number of potential grazing days varied across sites, from 15 to 78 and from 48 to 155 days per year under light and heavy grazing, respectively (Table 4). Under heavy grazing on the low-potential soil, 50% of the years had 164, 150 and 46 potential grazing days or more in Charlton, Hopetoun and Waikerie, respectively (Fig. 8). Under light grazing, at least 81 and 51 grazing days were possible in 50% of the years in Charlton and Hopetoun. Light grazing in Waikerie was possible in <40% of the years, with at least 1 month or 2 months of grazing in only 22% and 9% of the years (Fig. 8). As grass production is higher on the high-potential soil, the potential grazing period is longer, with average

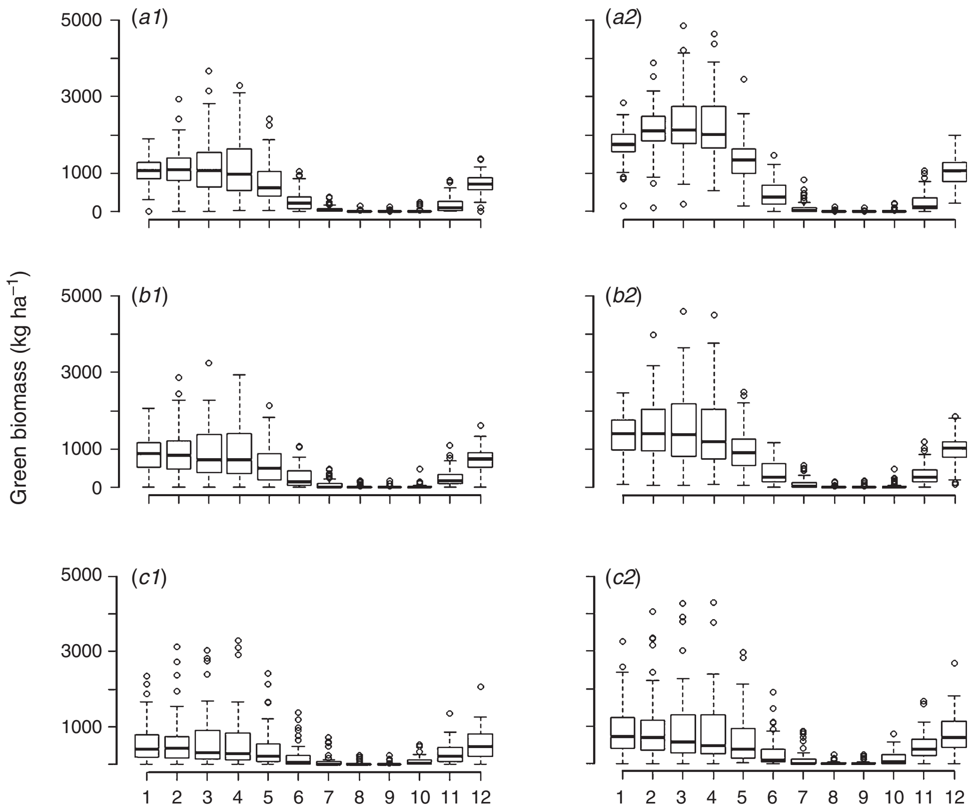

Fig. 6. Boxplots (median, quartile, decile and extreme values) of predicted green biomass per month for a summer-growing perennial grass pasture at (*a*) Charlton, (*b*) Hopetoun and (*c*) Waikerie on a low-potential (1, left) and high-potential (2, right) soil for 1951–2010.

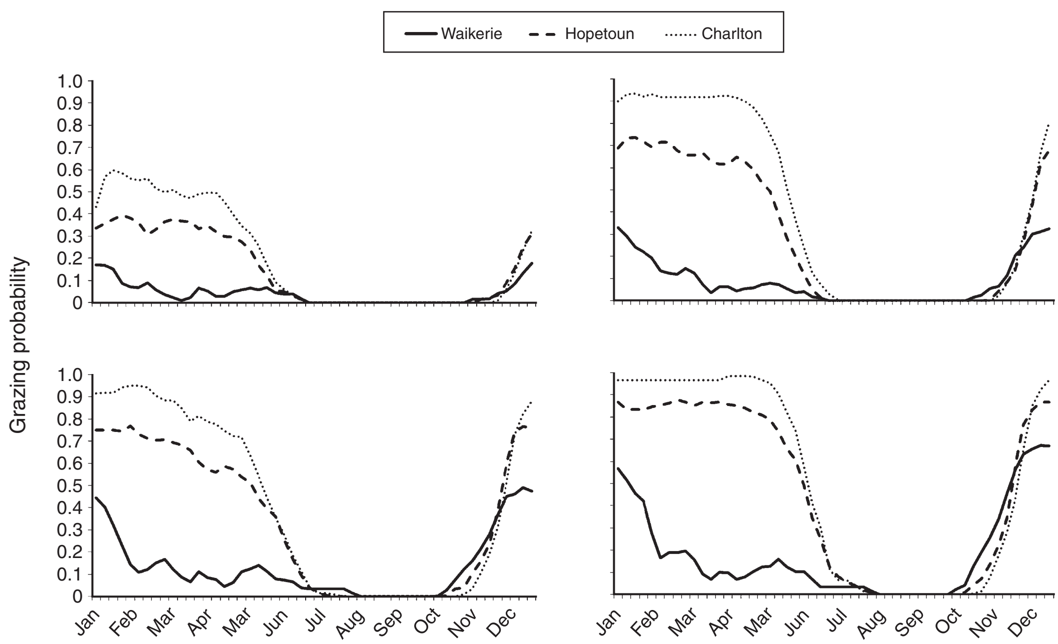

Fig. 7. Potential grazing probability for a summer-growing perennial grass pasture for three locations on a low-potential (left) and high-potential (right) soil for 1951–2010. The minimum green biomass threshold is 1000 kg ha^{-1} for the upper panes and 500 kg ha^{-1} for the lower panes.

Table 4. Average potential grazing days per year for three locations in the Mallee, a high-potential (HPS) and a low-potential (LPS) soil, and two minimum green biomass thresholds (1000 and 500 kg ha^{-1}), based on pasture simulations for 1951–2010

	Light grazing, threshold 1000 kg ha^{-1}		Heavy grazing, threshold 500 kg ha^{-1}	
	LPS	HPS	LPS	HPS
Charlton	78	156	155	193
Hopetoun	57	114	131	174
Waikerie	15	31	48	67

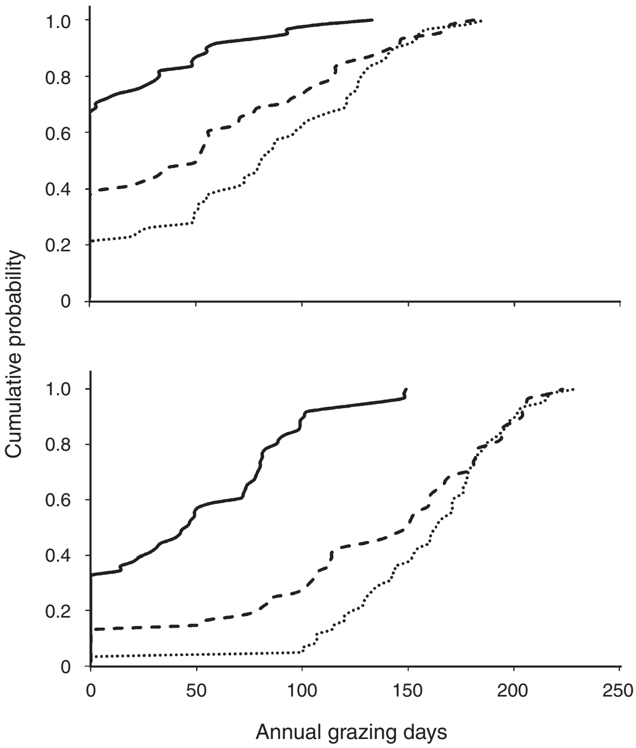

Fig. 8. Cumulative distribution functions for the annual (July–June) potential grazing days for Charlton (. . .), Hopetoun (– – –) and Waikerie (—) with a minimum green biomass threshold of 1000 kg ha^{-1} (upper) and 500 kg ha^{-1} (lower), based on pasture simulations for a low-potential soil for 1951–2010.

grazing days across sites 31–156 and 67–193 under light and heavy grazing, respectively (Table 4).

Discussion

Grasses with active summer growth require high soil temperatures (>15–18°C) and adequate moisture for successful germination and seedling establishment (Moore and Barrett-Lennard 2006; Nie *et al*. 2008). In southern Australia, these conditions are met only in early spring or late autumn. Risks of failure are associated with both seasons; grasses sown in autumn will become dormant in the immature stage and have to compete with annual volunteer weeds, whereas in spring the risk of a dry topsoil is high (Moore *et al*. 2006; Corleto *et al*. 2009). Overall, the spring sowing in the trials resulted in good establishment at Hopetoun and poorer establishment at Karoonda in locations where water repellency in the non-wetting sands led to dry topsoils and poor germination.

The long-term persistence of the grasses in the trial at Hopetoun shows that the selected cultivars can tolerate the long, dry summers and cold, wet winters typical for the region. Together with the reasonable biomass production, this would warrant the costs associated with pasture establishment. It should be noted that there was no recruitment from seed, and the trials were ungrazed, so persistence under grazing remains to be tested. The good persistence of the grass species at Hopetoun over 6 years is in line with other experimental experience for both *Panicum maximum* and Rhodes grass cultivars (Harris *et al*. 2009). Boschma *et al*. (2009) also found good persistence for several subtropical perennial grasses in trials in northern New South Wales (NSW). For trials in Italy, good persistence of subtropical perennials (Gherbin *et al*. 2007; Corleto *et al*. 2009) confirmed that these species are drought-resistant, tolerant to cold winter conditions, and adapted to marginal soils not often used for cropping (Smith 1986). However, the low persistence of *P. coloratum* cv. Bambatsi (25% over 3 years) in the study by Harris *et al*. (2009) did not correspond with the good persistence displayed by this cultivar at Hopetoun. In addition, the poor persistence of Rhodes grass in trials described by Nie *et al.* (2008) was not in line with our observations. There are various possible reasons for the differences. Pasture persistence is related to management, including the management of soil fertility, grazing intensity, and weed and pest control, as well as environmental factors such as rainfall, temperature and soil type (Nie *et al*. 2008; Boschma *et al*. 2009). Site differences, especially related to the environmental conditions during winter, are important too, because subtropical grasses are intolerant to low temperatures in combination with incidental frosts and wet soils (Moore *et al*. 2006; Reed *et al*. 2008).

Comparing biomass production in the trials at Hopetoun and Karoonda with values reported in the literature is of limited value, as different conditions usually result in much different biomass production than we found. For example, the biomass production data from Italy (Gherbin *et al*. 2007; Corleto *et al*. 2009) were recorded in trials in wetter areas (450–900 mm), where irrigation and high fertiliser rates were used. Trial data from NSW and WA also indicate much higher biomass than in our experiments, mainly due to higher rainfall (e.g. Nie *et al.* 2008; Reed *et al.* 2008). Nonetheless, the fact that biomass production in the first wet year at Karoonda remained far below the peak at Hopetoun is in line with similar observations of slow establishment and low biomass production in the first year of Italian trials (Gherbin *et al*. 2007; Corleto *et al*. 2009).

The model performance statistics were worse than for more mainstream pasture species in the region, such as *Medicago* spp. (see Robertson 2006*b*), which have received more research attention so far. However, a GRAZPLAN validation for native grassland species (Moore *et al.* 2010) demonstrated model performance comparable to the current study. Overall, the performance of GRAZPLAN was acceptable in terms of predicting both the magnitude of pasture biomass and the timing of growth of the C4 grasses in this study. The latter is important to accurately assess within-season forage availability and the contribution of different feed sources to the farm feed-base (Moore *et al*. 2009). Prediction of biomass production in the first year of establishment was relatively accurate for the average of all cultivars (Fig. 4). However, the generic C4 grass parameter set did not capture the differences in early biomass production between cultivars (Fig. 2, 4). After the first year, cultivars behaved much more similarly, and model accuracy was higher. Except for ATF-714, the biomass peak after the wet 2010–11 summer was under-predicted by the model. However, as the wet conditions in 2010–11 were exceptional for the Mallee, and model predictions for the other 5 years were sufficiently accurate, we can safely conclude that the model is adequate for use in Mallee climate conditions. Moreover, as biomass production was not consistently and statistically different between the four *Panicum* and *Megathyrsus* cultivars, the model is adequate for the simulation of biomass production by these cultivars if grown in conditions similar to the Hopetoun trial. When grown in more conducive, wetter environments, where differences have been recorded between cultivars (e.g. Moore *et al*. 2006; Corleto *et al*. 2009), cultivar-specific parameter values based on more detailed measurements would be necessary. Measurements of forage quality aspects would also be required for greater confidence in model predictions of digestibility and its temporal evolution. Models predicting C4 grass biomass production were used in other temperate regions, such as the US. Several studies report on simulations of switchgrass (*Panicum virgatum* L.), a crop used in the bio-energy industry (Kering *et al*. 2012). For three models, IFSM (Corson *et al*. 2007), ALMANAC (Kiniry *et al*. 2008) and EPIC (Brown *et al*. 2000), model performance in predicting switchgrass productivity was acceptable. However, the simulation of the seasonal distribution and the year-to-year variation of yield remained inaccurate in those applications (Corson *et al*. 2007), whereas the GRAZPLAN model showed good performance in terms of simulating the timing of pasture growth. For multiple harvests per year, accurate predictions of switchgrass biomass were not obtained. In this study, we did not predict, or measure, biomass production under frequent grazing or mowing. To improve the validity of the model outputs, future research should consider the impacts of grazing on persistence.

Similar to the findings in WA (Lawes and Robertson 2008; Finlayson *et al*. 2012), the niche for summer-active perennial grasses in Mallee mixed farming systems is likely to be on the more marginal soils where other broadleaved perennials (e.g. lucerne) are not well adapted and where cropping activities are inherently risky. Model simulations of biomass growth indicate that, on such marginal soils, green biomass is likely to be available from December to May. In at least 40% of the years, biomass availability would allow grazing for 2 and 3 months in areas with October–April rainfall of 175 and 225 mm, respectively (Table 4, Fig. 8). These probabilities refer to very marginal soil conditions (plant-available water capacity of 63 mm and rooting depth of 0.6 m) and light grazing pressure using a rather high green-biomass threshold of 1000 kg ha^{-1}. Lowering the threshold to 500 kg ha^{-1} of green biomass would double the average potential grazing days in these areas, as would more favourable soil conditions. However, in very dry regions similar to Waikerie where October–April rainfall is <150 mm, the potential of summer-growing grasses to provide feed is very low, with no chance for grazing in 33–67% of the years, depending on the green-biomass threshold (Fig. 8). In the model simulations, pasture growth during winter was not included, resulting in a likely overestimation of the moisture storage in the soil profile. In a commercial paddock situation, winter growth is desirable, and thus the model predictions probably overestimate the real grazing potential. However, given the good match between observations and predictions (Fig. 3), the mismatch is limited.

Production of C4 grasses in the Mallee is episodic, with large annual variability associated with the variable climate, so that even in the wetter areas of the region there will be a fraction of years with little or no grazing. This means that supplementary feeding would still be required, but in smaller amounts and in fewer years. The variable nature of summer-growing perennial pasture production requires great management agility (Bell and Moore 2012) to exploit the feed resources effectively. However, with a high marginal value of forage when feed is scarce (Finlayson *et al*. 2012), the timing of the high grazing probabilities seems favourable. The digestibility and protein content of summer-growing perennial grass pastures is often modest (Wilson and 't Mannetje 1978), but alternative sources of forage during summer and autumn (i.e. annual pasture residues and cereal stubbles) are of lower nutritive value (McIvor and Smith 1973; Wales *et al*. 1990). Therefore, farmers have to deal with a management trade-off between using the C4 grass forage in late spring when it is of high quality and retaining it for use in autumn when the forage marginal value is highest. The use of a validated pasture model can help to inform such decisions.

Conclusion

On-farm field experiments and simulation modelling showed that summer-growing perennial pastures have considerable potential to narrow summer–autumn feed gaps in mixed cereal–sheep farming systems in the Mallee region of southern Australia. Given the persistence and reasonable biomass production potential of several *Panicum* and *Megathyrsus* spp., the high costs of pasture establishment would be offset. The niche for summer-growing perennial pastures is restricted to areas that receive >150 mm of rainfall from October to April and to marginal soils where cropping is too risky. Under these conditions, grazing would be possible for 2–3 months in at least 40% of the years. Simulation modelling, indicating high growth rates in response to warm temperatures and moisture availability, showed high potential grazing probability throughout summer and early autumn, when alternative feed sources are in low supply and of low nutritive value. Future work should be directed at investigating the effects of grazing on pasture performance and testing model performance in this respect and with regard to feed quality predictions.

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