CSIRO PUBLISHING
www.publish.csiro.au/journals/ajar Australian Journal of Agricultural Research, 2008, 59, 761–768

Simulating pasture growth rates in Australian and New Zealand grazing systems

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Abstract. DairyMod, EcoMod, and the SGS Pasture Model are mechanistic biophysical models developed to explore scenarios in grazing systems. The aim of this manuscript was to test the ability of the models to simulate net herbage accumulation rates of ryegrass-based pastures across a range of environments and pasture management systems in Australia and New Zealand. Measured monthly net herbage accumulation rate and accumulated yield data were collated from ten grazing system experiments at eight sites ranging from cool temperate to subtropical environments. The local climate, soil, pasture species, and management (N fertiliser, irrigation, and grazing or cutting pattern) were described in the model for each site, and net herbage accumulation rates modelled. The model adequately simulated the monthly net herbage accumulation rates across the range of environments, based on the summary statistics and observed patterns of seasonal growth, particularly when the variability in measured herbage accumulation rates was taken into account. Agreement between modelled and observed growth rates was more accurate and precise in temperate than in subtropical environments, and in winter and summer than in autumn and spring. Similarly, agreement between predicted and observed accumulated yields was more accurate than monthly net herbage accumulation. Different temperature parameters were used to describe the growth of perennial ryegrass cultivars and annual ryegrass; these differences were in line with observed growth patterns and breeding objectives. Results are discussed in the context of the difficulties in measuring pasture growth rates and model limitations.

Additional keywords: DairyMod, EcoMod, SGS Pasture model, simulation models.

Introduction

The behaviour of pastoral systems arises from complex interactions among soils, plants, and animals, and is strongly influenced by weather and management. While each of these components can be studied in isolation, the results are not always in accord with observations taken at the level of the whole system. Farmlet experiments can be used to study whole-system behaviour but such experiments can generally only be maintained for 3–5 years. This is a relatively short period compared with the natural variation caused by weather, or with the length of time that it can take for soil organic matter pools to equilibrate to new management (Jenkinson 1990). Simulation models are one of the few methods of incorporating all the elements of the system, which also allows investigation of the system over many years. However, if they are to be used in this way, we must know how much confidence can be placed in the simulation of the components of the system. In particular, for grazing systems, the model must be capable of simulating the temporal dynamics of pasture growth and removal, since this drives many other key system properties such as nutrient cycling, organic matter accumulation or loss, and animal intake.

DairyMod, EcoMod, and the SGS Pasture Model are mechanistic biophysical models developed for the Australian and New Zealand grazing industries (Johnson *et al*. 2003, 2008). Each of the models has the same underlying biophysical simulation model with alternative interfaces, varying primarily in the available paddock and farm management options that can be selected for their intended uses. Hereafter in this paper, this suite of models is referred to as 'the model', following the convention of Johnson *et al*. (2008). The model uses daily weather information and comprises soil water, soil nutrient, pasture growth, and animal production modules. It has been developed for the purpose of providing scientists with the ability to explore the interrelationships between these modules

 10.1071/AR07371 0004-9409/08/080761

either in a whole systems context, or as individual components. The model is sufficiently versatile to simulate the range of environments represented by the pastoral regions of Australia and New Zealand, to differentiate between forage species, and to offer several options for the management of the grazing system (Johnson *et al*. 2008).

The aim of the study reported here was to assess whether the model can satisfactorily simulate pasture growth rates by comparing measured and modelled net herbage accumulation rates from 10 grazing system experiments across Australia and New Zealand. Since newer ryegrass cultivars have been bred for increased growth rates at lower temperature than older cultivars (Cunningham *et al*. 1994), a second objective was to evaluate the effect of temperature parameters in the model on growth rate of two perennial ryegrass ecotypes.

Materials and methods

Pasture growth rate datasets

Pasture growth rate datasets were collated for a range of environments, soil types, and management systems across Australia and New Zealand (Table 1). The pastures were all based on either perennial ryegrass (*Lolium perenne*) or annual ryegrass (*L. multiflorum*) and, at the temperate sites, were sown with white clover (*Trifolium repens*). The environments ranged from cool temperate climates in Tasmania and New Zealand to subtropical regions of south-eastern Queensland. The pasture management systems included a range of grazing and cut trials that were either dryland or irrigated, to which nitrogen (N) fertiliser was applied at rates varying between 0 and 667 kg N/ha.year (Table 1).

The soil type, mean rainfall, pasture species and ryegrass cultivar, experimental period, number of replicates or paddocks, amount of N and irrigation applied, and the number of times cut or grazed per year for each source of measured growth rates are summarised in Table 1. Herbage mass was estimated in each of the grazed experiments using the calibrated rising plate meter method (Earle and McGowan 1979) and by destructive harvests in the cut trials. The location and climate of each site, and a brief description of cutting or grazing management are provided below.

- Ellinbank (SE Vic.; 38°15′S, 145°93′E; temperate climate). Growth rates were calculated from 5 exclusion cages randomly placed across the farmlets, which were harvested at 2–4 week intervals during spring and 4–5 week intervals during the rest of the year. Farmlets were grazed at a stocking rate of 2.0–2.5 Holstein-Friesian cows/ha, with grazing based on a pre-grazing herbage mass of 2.4–2.6 t dry matter (DM)/ha and a target post-grazing residual of 1.4–1.6 t DM/ha (DARA 1989).
- Terang (SW Vic.; 38°16′S, 142°53′E; temperate climate). Growth rates were calculated from a 16 ha farmlet trial that was grazed at a stocking rate of 2.25 Holstein-Friesian cows/ha. Grazing management was based on a leaf-stage rotation, with a silage cutting window between 10 October and 31 December (Chapman *et al*. 2007).
- Elliott (NW Tas.; 41°06′S, 145°46′E; cool temperate climate).
    - Cut trial: growth rates were calculated from a replicated irrigated water-use efficiency trial. Plots were harvested at the 2–3 leaf stage for perennial ryegrass to a residual of 1.5 t DM/ha (Donaghy *et al*. 2006).
    - Dryland farmlet: growth rates were calculated from a 35-ha farmlet grazed at 2.25 cows/ha. Grazing management was based on a leaf-stage rotation (grazed at the 2–3-leaf stage of regrowth), with a silage cutting window from 1 October to 31 December (Donaghy 2007*a*).
    - Irrigated farmlet: growth rates were calculated from a 16.5-ha farmlet grazed at 4.25 cows/ha. Grazing management was based on a leaf-stage rotation (grazed at the 2–3-leaf stage of regrowth), with a silage cutting window from 1 October to 31 December (Donaghy 2007*a*).

Table 1. Description of the experimental sites and management systems used to provide the measured net herbage accumulation rate data, including soil type, mean annual rainfall (mm) for the experimental period, pasture species and ryegrass cultivar, experimental period for growth rates reported, number of replicates or paddocks, and annual N fertiliser applied (kg/ha), number of times cut or grazed, and irrigation applied (ML/ha), as well as the source of the measured data

PRG, Perennial ryegrass; ARG, annual ryegrass; WC, white clover

Site	Soil type	Rainfall	Species	Ryegrass cultivar	Years	No. reps or paddocks	N applied	No. cuts or grazings	Irrigation	Herbage accumulation rate data source
Ellinbank	Red Mesotrophic Haplic Ferrosol[A]	1190	PRG/WC	Victorian	iv.86–xii.89	5	0	12	0	DARA (1989)
Terang	Brown Chromosol[A]	519	PRG/WC	GR Impact	vi.05–xii.06	20	124	8–11	0	Thamaraj *et al*. (2007)
Elliott	Red Mesotrophic Haplic Ferrosol[A]	1074	PRG	GR Impact	i.04–xii.05	4	500	8–10	4.0	Donaghy *et al*. (2006)
			PRG/WC	GR Impact	vii.03–vi.06	44	100–140	6–9	0	Donaghy (2007*b*)
			PRG/WC	GR Impact	vii.03–vi.06	26	250–320	8–11	4.0	Donaghy (2007*b*)
Palmerston North	Weathered Fluvial Recent[B]	971	PRG/WC	Unknown	xi.96–vii.99	20	104–115	8–14	0	Garcia and Holmes (2005)
Windsor	Mottled Fragic Pallic[B]	624	PRG/WC	Ruanui	ix.78–viii.81	4	0	26	0	Cossens (1990)
Camden	Brown Chromosol[A]	646	ARG/kikuyu	Surrey	iii.04–xi.06	4	536–667	18–20	7.2–7.7	Garcia (unpublished)
Mutdapilly	Black Vertesol[A]	587	ARG	Flanker	iv.00–xii.03	3	550	11	6.0	Lowe *et al*. (2007)
Gatton	Black Vertesol[A]	622	PRG	GR Impact	iv.98–v.04	3	550–600	11–12	8.0	Lowe *et al*. (2008)

[A]Isbell (1996). [B]Hewitt (1998).

- Palmerston North (North Island, NZ; 40°24′S, 175°37′E; temperate climate). Growth rates were calculated from a farmlet trial examining time of calving. Farmlets were stocked at 2.0–2.5 cows/ha, with grazing based on a pre-grazing herbage mass of >2.6 t DM/ha and a post-grazing residual of >1.6 t DM/ha (Garcia and Holmes 2005).
- Windsor (South Island, NZ; 45°1′S, 170°48′E; cool temperate climate). A pasture growth rate trial, grazed by sheep. Cages (3 m^2) were used to exclude small areas from grazing. The area under each cage was trimmed before the cage was fixed in place and harvested at 4–6 week intervals to a residual of 1.0 t DM/ha. Cages were moved onto new areas after each grazing (McNamara 1992).
- Camden (NSW; 34°04′S, 150°69′E; warm temperate climate). Growth rates for the annual ryegrass phase of a replicated annual ryegrass/kikuyu (*Pennisetum clandestinum*) grazing trial were used. Grazing rules aimed to defoliate pastures at the 2–3 leaf stage for annual ryegrass, coinciding with pre- and post-grazing biomasses of 2.4–2.6 and 1.3–1.5 t DM/ha, respectively (Garcia *et al*. 2006).
- Mutdapilly/Gatton (SE Qld; 27°46′S, 152°40′E/27°34′S, 152°20′E; subtropical climate). Growth rates were calculated from trials comparing cultivars of annual (Lowe *et al*. 2007) and perennial ryegrass (Lowe *et al*. 2008). Plots were defoliated at 4-week intervals until the beginning of spring at which time the cutting interval was reduced to 3 weeks. For perennial ryegrass, monthly growth rates were calculated using the first year of growth after each sowing to minimise the effect of species persistence on the measured growth rates.

For each dataset, the monthly average of the daily net herbage accumulation rate (kg DM/ha.day) was calculated to test the ability of the model to simulate seasonal growth patterns on a time-scale that is relevant to decision makers in the intensive grazing industries. Daily net herbage accumulation rates were calculated from the DM yield between harvest dates in the cut trials and based on estimates of the difference between pre- and post-grazing herbage masses in the farmlet trials. The exception was in the farmlet trials at Elliott where daily net herbage accumulation was calculated from weekly herbage mass estimates in each paddock. In all of the measured datasets, periods of net negative growth rate (i.e. when senescence exceeds growth) were reported as having zero net herbage accumulation. The measured data presented are the average of the 3–4 replicates for the experiments that used cutting and 4–44 grazed paddocks in the farmlet experiments. The variability of measured monthly net herbage accumulation rates is reported as either the range or the 10th and 90th percentiles, except for the Ellinbank and Windsor sites where only the average data were available. Accumulated yields were calculated from the average net herbage accumulation rates.

Model simulations

Daily climate data for each Australian site were obtained from the Bureau of Meteorology SILO database (Jeffrey *et al*. 2001), while climate data for Palmerston North and Windsor in New Zealand was obtained from NIWA (NIWA 2004). The simulations were developed in the model in conjunction with researchers at each site in order to ensure appropriate representation of the climate, soil type, and pasture management (Table 1). The modelled herbage accumulation rate data are presented as the monthly mean daily net herbage accumulation (growth minus senescence) after adjusting days with net negative herbage accumulation rate to equal zero. This approach aligned the methods used to report predicted growth rates with the methods used to report herbage accumulation rate measured in the field.

Ryegrass growth parameters

To simulate the growth of the perennial ryegrass cultivars used in the pasture growth rate experiments (Table 1), parameter sets were developed for a winter-dormant (Victorian) and winter-active (GR Impact) perennial ryegrass cultivar. In the model, plant growth responses to temperature are described by a generic empirical curve defining the minimum, optimum, and maximum temperatures for photosynthesis based on a representative day-time temperature, and an effect of extreme low and high temperatures that simulate growth restrictions in response to frost and high-temperature stresses, respectively (Johnson 2007). For perennial ryegrass, parameters for cv. GR Impact were developed by modification of low-temperature photosynthesis responses for cv. Victorian (Table 2). These parameters were tested against the Elliott cut trial dataset, using a ‘trial and error’ approach with the parameter settings that showed the best fit applied to other datasets without further adjustment. A lower minimum temperature threshold for photosynthesis was used for annual ryegrass (Table 2), reflecting its higher potential growth rate at low temperatures compared with perennial ryegrass cultivars (Mitchell 1954). To simulate annual ryegrass, the model also requires that the dates of earliest emergence and anthesis be defined, along with the number of days between anthesis and maturity (Johnson 2007). The parameter settings for the perennial ryegrass cultivars and annual ryegrass are shown in Table 2 for dryland and irrigated conditions. The only other parameter difference used to simulate ryegrass growth in this study was to inactivate the extreme high-temperature responses when the pasture was irrigated (Table 2), moderating the high-temperature growth restriction under irrigated conditions.

Data analyses

Several approaches were taken to analyse the measured and predicted net herbage accumulation rates. First, a visual

Table 2. Temperature parameters (°C) used for perennial and annual ryegrass cultivars in the model, under dryland and irrigated conditions

Cultivar/management	Photosynthesis/ respiration		Extreme temperature	
	Minimum	Optimum	Low	High
	Perennial ryegrass			
Victorian/dryland	5	20	Active	Active
GR Impact/dryland	3.5	20	Inactive	Active
GR Impact/irrigated	3.5	20	Inactive	Inactive
	Annual ryegrass			
Dryland	1	20	Active	Active
Irrigated	1	20	Active	Inactive

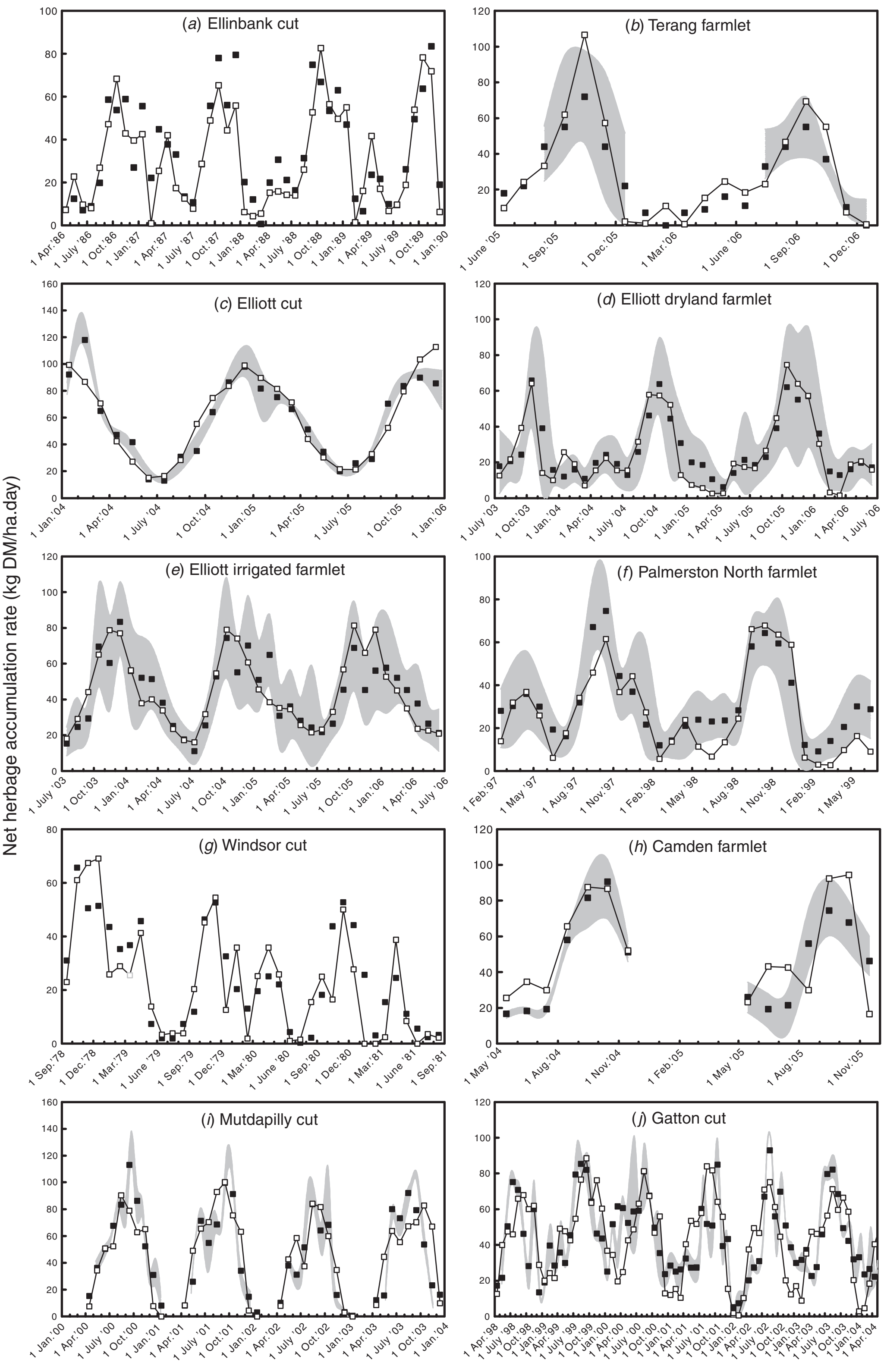

Fig. 1. Measured (■) and modelled (□) monthly mean daily net herbage accumulation rates (kg DM/ha.day), including measured variability (grey shaded) where available as indicated in parentheses, for (*a*) Ellinbank cut trial, (*b*) Terang farmlet (range), (*c*) Elliott cut trial (range), (*d*) Elliott dryland farmlet (10/90 percentiles), (*e*) Elliott irrigated farmlet (10/90 percentiles), (*f*) Palmerston North farmlet (10/90 percentiles), (*g*) Windsor cut trial, (*h*) Camden famlet (range), (*i*) Mutdapilly cut trial (range), and (*j*) Gatton cut trial (range).

inspection of the seasonal pattern was conducted as a commonsense evaluation of the patterns for each simulation (including maximum and minimum net herbage accumulation rates, seasonal patterns, and how often the modelled herbage accumulation rate was outside of the range of herbage accumulation rates measured in each experiment). Second, a Bland-Altman plot (Bland and Altman 1986) was drawn for all data to highlight the magnitude of the difference between the mean measured and modelled monthly growth rates at each site. Third, a range of model evaluation statistics were calculated, based on the work of Tedeschi (2006), to compare the mean measured and predicted monthly net herbage accumulation rates and seasonal yields. These statistics were calculated separately for all of the data, data from temperate (Ellinbank, Terang, Elliott, Palmerston North, and Windsor) and warm temperate/subtropical (Camden, Mutdapilly, and Gatton) sites separately, and data for each season separately to test the accuracy of the simulations in different environments and seasons. The statistics calculated were: mean bias, the difference between measured and simulated mean; r^2, coefficient of determination; mean prediction error (MPE), a measure of general model efficiency expressed as % of mean (Bibby and Toutenburg 1977); model efficiency (MEF), the proportion of variation explained by the modelled value with a value of 1 indicating a perfect fit; Variance ratio (v), the amount of variance in the measured and modelled datasets with a value of 1 indicating the same amount of variance; bias correction factor (C_b), which indicates bias from the $y = x$ line with a value of 1 indicating no bias; and the concordance correlation coefficient (CCC), which is a simultaneous measure of accuracy and precision with an ideal fit indicated by a value of 1. Further details of these statistics are available in Tedeschi (2006). The Bland-Altman plot and the model comparison summary statistics all assume that there is no error in the measured net herbage accumulation rates.

Results

The measured and simulated monthly net herbage accumulation rate comparisons for each dataset are presented in Fig. 1. Visual inspection of these figures indicates that seasonal patterns and maximum and minimum herbage accumulation rates are similar for the predicted and observed data. The modelled herbage accumulation rates were more often within the measured range in temperate than in warm temperate/subtropical environments (Fig. 1). This observation is confirmed by the Bland-Altman plot (Fig. 2), which shows that 15 of the 18 data points where the difference between the measured and modelled data was greater than ± 2 standard deviations were from the warm temperate and subtropical environments.

The summary statistics presented in Table 3 indicate model performance across all data, temperate and warm temperate/subtropical environments, and individual seasons. Across all of the datasets the mean bias ranged from –3.7 to 6.3 kg DM/ha.day and the MPE from 28 to 46% (Table 3), with the highest deviations recorded in summer and autumn seasons. MEF was greater than 0.5 for all datasets except for the autumn and spring seasons. The C_b and v statistics indicated, respectively, that there were only small deviations from the 1 : 1 line, and that the variance

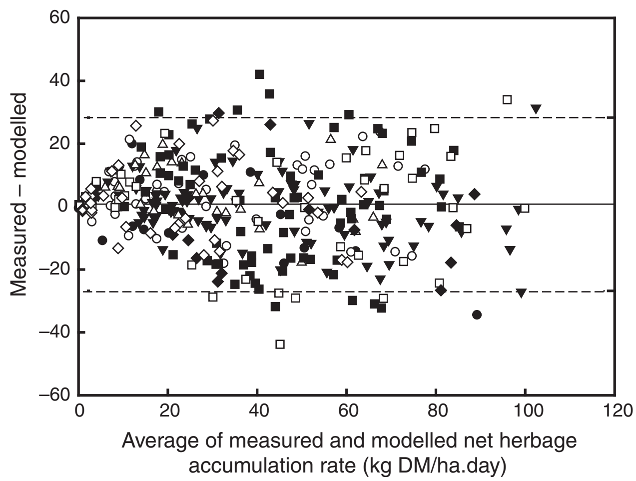

Fig. 2. Bland-Altman plot for Ellinbank (○), Terang (●), Elliott (▼), Palmerston North (△), Mutdapilly (□), Gatton (■), Camden (◆), and Windsor (◇) monthly mean daily net herbage accumulation rates. The solid line indicates the mean difference between measured and modelled net herbage accumulation rates, and the dashed lines show the mean ± 2 s.d.

Table 3. Summary statistics indicating model performance for monthly mean daily net herbage accumulation rates (all data, data for temperate and warm temperate/subtropical environments, and data for each season) (kg DM/ha.day) and accumulated yield (Accum. yield, t DM/ha)

MPE, Mean prediction error; MEF, modelling efficiency; V, variance ratio; Cb, bias correction factor; CCC, concordance correlation coefficient

	Monthly mean daily net herbage accumulation rate							Accum. yield
	All data	Temperate	Warm temperate/ subtrop.	Summer	Autumn	Winter	Spring	Year/season
Measured mean	38.49	34.65	45.29	34.46	26.63	34.20	57.21	13.11
Simulated mean	37.73	33.28	45.63	28.12	26.43	33.25	60.88	12.85
Mean bias	0.76	1.37	−0.34	6.33	0.20	0.95	−3.67	0.25
r^2	0.73	0.82	0.58	0.79	0.45	0.80	0.43	0.88
MPE	35.8	31.4	39.3	41.8	46.0	33.2	28.9	10.8
MEF	0.68	0.78	0.50	0.68	0.26	0.80	0.27	0.87
V	0.93	0.91	0.97	0.89	0.91	1.05	0.98	0.98
C_b	1.00	1.00	1.00	0.99	1.00	1.00	1.00	1.00
CCC	0.85	0.90	0.76	0.88	0.66	0.89	0.66	0.94
n	352	225	127	79	86	94	93	31

in the modelled data was similar to that in the measured data, across all of the datasets (Table 3).

In general, the modelled predictions were better in the temperate than in the subtropical environment (higher r^2, MEF, CCC, and lower MPE; Table 2), and in summer and winter seasons than in autumn and spring (higher r^2, MEF, CCC; Table 3).

The accumulated seasonal yields for each of the monthly growth rate comparisons are shown in Table 4. The measured yields were 5.8–21.7 t DM/ha. The simulated yield was within ± 10% of the measured yield in 17 of the 31 seasons, while two seasons had a modelled yield that was >± 20% of the measured value (Table 4). The model performance summary statistics for accumulated yield indicated closer agreement than for the monthly growth comparisons (lower MPE, higher r^2, higher MEF; Table 3).

The effect of the temperature parameters used to describe the differences between the Victorian and GR Impact perennial ryegrass cultivars (Table 2) on mean monthly pasture growth rate at Terang is shown in Fig. 3. On a percentage basis the differences between the cultivars were greatest in winter (53%) followed by spring, autumn, and summer (increases of 20, 9, and 2%, respectively). The simulated long-term average annual DM production of cv. Grasslands Impact was 20% more than of cv. Victorian at this site.

Table 4. Measured and modelled accumulated yields (t DM/ha) and percentage difference for each of the comparisons

Site	Period	Accumulated yield Measured	Accumulated yield Modelled	% difference
Ellinbank	iv.86–iii.87	11.4	10.4	−9.3
	iv.87–iii.88	12.9	10.3	−20.4
	iv.88–iii.89	13.5	12.1	−10.0
	iv.89–xii.89	9.4	9.3	−0.8
Terang	vi.05–v.06	9.6	10.6	9.9
	vi.06–xii.06	5.8	6.8	15.9
Elliot – cut	i.04–xii.04	21.5	21.3	−0.9
	i.05–xii.05	21.7	22.5	3.7
Elliot – dryland	vii.03–vi.04	8.7	8.1	−6.3
	vii.04–vi.05	9.6	8.6	−10.3
	vii.05–vi.06	11.3	11.4	0.6
Elliot – irrigated	vii.03–vi.04	15.9	15.8	−0.4
	vii.04–vi.05	15.9	15.7	−1.4
	vii.05–vi.06	15.3	16.4	6.9
Palmerston North	vii.97–vi.98	11.8	10.0	−15.2
	vii.98–vi.99	11.8	10.4	−12.4
Mutdapilly	iv.00–i.01	16.6	13.7	−17.3
	iv.01–i.02	14.4	16.1	12.2
	iv.02–i.03	11.2	12.5	11.8
	iv.03–xii.03	13.6	14.3	5.4
Gatton	iv.98–iii.99	14.3	15.1	5.4
	iv.99–iii.00	19.8	19.8	−0.1
	iv.00–iii.01	17.3	14.6	−15.3
	iv.01–iii.02	13.4	15.7	17.5
	iv.02–iii.03	16.8	14.6	−13.3
	iv.03–iii.04	16.2	15.2	−6.2
Camden	v.04–xi.04	10.3	11.7	13.8
	v.05–xi.05	9.6	10.5	9.9
Windsor	ix.78–viii.79	11.5	11.2	−3.1
	ix.79–viii.80	7.6	8.4	9.9
	ix.80–viii.81	7.6	5.3	−30.3

Discussion

These results show that the model can realistically simulate the monthly herbage accumulation rates and seasonal yields of ryegrass-based pastures in both temperate and subtropical environments, across a range of soil types and pasture management options, including cutting and grazing systems (Fig. 1). In addition, the Elliott dryland (Fig. 1*d*) and irrigated (Fig. 1*e*) farmlet simulations demonstrated the ability of the model to simulate herbage accumulation rates when different N fertiliser and irrigation management strategies were applied in the same seasons. When the entire dataset of monthly growth rates was considered, the mean bias was 0.4 kg DM/ha.day with a MPE of 36%. While a MPE of less than 20% is generally considered to indicate adequate model accuracy, these results are within the range of those observed in similar studies with other grazing system models (Dolling *et al.* 2005; Jouven *et al.* 2006; Robertson 2006). The other summary statistics presented in Table 3 all indicated more than adequate simulation of the measured data and show that most of the difference between measured and modelled herbage accumulation rates is due to random variation. Model predictions were more accurate and precise in the temperate than in the warm temperate/subtropical environments, and in winter and summer than in autumn and spring (Table 3). Accumulated pasture yields (Table 4) were predicted with greater accuracy than monthly growth rates due to compensation between over-prediction of monthly growth rates in spring and under-prediction during summer (Table 3).

One of the difficulties in comparing the measured and modelled herbage accumulation rates is that this comparison does not take into account sources of variability in the measured data, which also contribute to the differences between measured and modelled data. These sources of variation arise from the difficulties of accurately estimating herbage mass (Frame 1993; Cosgrove *et al.* 1998), as well as variability across paddocks caused by differences in herbage mass associated with grazing (Hirata 2000) and soil variation. This is a particular issue when using farmlet data that are averaged across numerous paddocks. This variability is represented by the range or percentiles, where available, in Fig. 1. It is not possible to

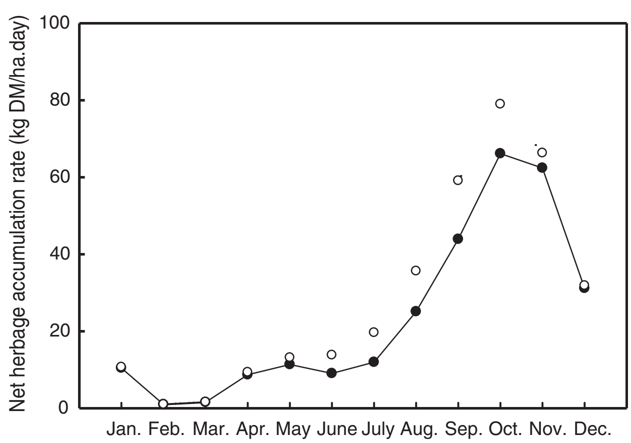

Fig. 3. Effect of Victorian (●) and GR Impact (○) perennial ryegrass parameters on mean net herbage accumulation rates (1961–2006) at Terang. Simulation is based on a monthly cut trial and soil nutrients are not limiting.

quantify how much of the difference between the measured and modelled data is due to errors in the measured data; however, it is evident that when the variability of measured data is presented, the modelled growth rates are usually within that range, even when they are different from the mean (Fig. 1).

In addition to variation in the measured data, discrepancies between the measured and modelled herbage accumulation rates may also arise because of limitations in the model. There are several possible reasons for this. First, the model does not incorporate plant phenological development, so does not explicitly simulate the physiological changes that occur with reproductive development, e.g. accelerated growth rate and increased proportion of stem material (Sheehy *et al*. 1979; Callow *et al*. 2000). This may have particular relevance to the modelled spring herbage accumulation rates. Second, the model does not attempt to simulate perennial ryegrass plant persistence, so declining plant densities and associated reductions in pasture growth rate cannot be captured. This is a particularly important issue for perennial ryegrass in subtropical environments (Lowe *et al*. 1999). Fulkerson and Donaghy (2001) summarised the important role that carbohydrate reserves have in ryegrass regrowth and persistence, particularly in subtropical environments. The model does not explicitly account for plant carbohydrate reserves, which may explain some of the discrepancy between measured and modelled data. In addition, differences between measured and modelled data may arise because it is not possible to replicate in the model all of the short-term pasture management decisions made in the farming system experiments. While the model has flexibility to describe management within a year in up to four phases, there is little capability of adjusting grazing and irrigation management to simulate different strategies applied in successive years. This is an area that could be addressed in future development of the model.

The model parameters used to describe the differences between the Victorian and GR Impact perennial ryegrass cultivars (Table 2) effectively simulated the higher winter growth rates (Fig. 3) that these newer cultivars have been selected for (Cunningham *et al*. 1994). The simulated 20% annual yield difference between the cultivars was comparable with the average 10% advantage of pastures based on cvv. Aries, Embassy, and Vedette compared with cv. Victorian, measured over 4 years in the same region (Nie *et al*. 2004). The higher response in the model could have been due to optimal management being imposed, i.e. no soil nutrient limitations and a monthly cutting frequency.

Conclusions

DairyMod, EcoMod, and the SGS Pasture Model simulated the monthly growth patterns and seasonal yields of ryegrass-based pastures across a range of pasture management systems and climatic zones with reasonable accuracy. The observed accuracy and precision of model predictions fell within acceptable ranges, particularly when the variability of measured pasture growth was considered. This study has demonstrated the ability of the model to simulate a broad range of grazing systems and confirms its value in addressing questions that may obviate expensive field research.

Acknowledgments

We acknowledge the contribution of Karen Christie (University of Tasmania) in developing the initial Elliott simulations, and thank Dr Jay Tharmaraj (University of Melbourne) and Kevin Lowe and Tom Bowdler (Department of Primary Industries and Fisheries) for the pasture growth rate data that they provided. Dr Jeremy Bryant (AgResearch) provided assistance with the statistical analyses. This work was funded by Dairy Australia, Meat & Livestock Australia, and AgResearch, New Zealand. The New Zealand sites were funded by the New Zealand Foundation for Science, Research and Technology (contract C10X0319).

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Manuscript received 4 October 2007, accepted 28 April 2008