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Evaluation of a Whole-Farm Model for Pasture-Based Dairy Systems

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ABSTRACT

In the temperate climate of New Zealand, animals can be grazed outdoors all year round. The pasture is supplemented with conserved feed, with the amount being determined by seasonal pasture growth, genetics of the herd, and stocking rate. The large number of factors that affect production makes it impractical and expensive to use field trials to explore all the farm system options. A model of an in situ-grazed pasture system has been developed to provide a tool for developing and testing novel farm systems; for example, different levels of bought-in supplements and different levels of nitrogen fertilizer application, to maintain sustainability or environmental integrity and profitability. It consists of a software framework that links climate information, on a daily basis, with dynamic, mechanistic component-models for pasture growth and animal metabolism, as well as management policies. A unique feature is that the component models were developed and published by other groups, and are retained in their original software language. The aim of this study was to compare the model, called the whole-farm model (WFM) with a farm trial that was conducted over 3 yr and in which data were collected specifically for evaluating the WFM. Data were used from the first year to develop the WFM and data from the second and third year to evaluate the model. The model predicted annual pasture production, end-of-season cow liveweight, cow body condition score, and pasture cover across season with relative prediction error <20%. Milk yield and milksolids (fat + protein) were overpredicted by approximately 30% even though both annual and monthly pasture and supplement intake were predicted with acceptable accuracy, suggesting that the metabolic conversion of feed to fat, protein, and lactose in the mammary gland needs to be refined. Because feed growth and intake predictions were acceptable, economic predictions can be made using the WFM, with an adjustment for milk yield, to test different management policies, alterations in climate, or the use of genetically improved animals, pastures, or crops.
Key words: dairy system model, simulation, pasture

INTRODUCTION

Pastoral farms, where animals are fed by grazing, are effectively managed ecosystems with a large number of factors affecting production. The factors are biological, physical, and economic. A challenge for pastoral farming is to be profitable and sustainable, which is defined as maintaining the health of the animals and pastures and minimizing environmental effects (N leaching and emission of greenhouse gases). As a result of genetic improvements, in New Zealand and other temperate climates where animals can be grazed outdoors year round, animals and pastures have high production capacity but they require careful management to achieve this potential. Cows are generally calved in early spring so that their high feed demand near the beginning of lactation matches the period of greatest pasture growth. Pasture is supplemented with some conserved feed, with the actual amount being influenced by seasonal pasture growth, genetics of the herd, and stocking rate. Areas suffering summer droughts or other climate challenges are adopting management practices to minimize the seasonal risk, such as calving some animals in the fall, irrigation, arable cropping, or milking once a day. A challenge for the industry is to develop management systems for regions that greatly differ climatically. Because field trials are expensive, lengthy, and may be inconclusive due to uncontrolled variables including climate, models are required to aid in the development of these systems.

Factors that need to be considered in modeling farm systems include animal and plant physiology, feeding behavior such as selection and substitution, climate, pasture quantity and quality, and flexible management policies. Several farm system models have been developed with various emphases including feed production (Rotz et al., 1999), management (Cros et al., 2004), soil-pasture interactions (Johnson et al., 2003), and environ-

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mental effects (Cabrera et al., 2006). Most farm systems models treat the animals as one (or more) herds but herd-level modeling precludes individual differences due to genotype (Bryant et al., 2005). Although detailed models have been developed for animal nutrition (Weiss, 2002) and metabolism (Baldwin, 1995; Hanigan et al., 2006), these models have largely remained separate from farm system models.

One approach for modeling a farm system has been to link existing models for parts of the system with management, into a complete dairy system, called the whole-farm model (**WFM**; Wastney et al., 2002). Animals were modeled as individuals so that factors such as weight, age, and genetic merit, which have an impact on production, and therefore economics, could be evaluated. Furthermore, by modeling cow metabolism, more detailed questions relating to feed conversion and milk composition can be investigated (McNamara, 2003).

The purpose of the current study is to evaluate WFM against experimental data from a farm system trial.

MATERIALS AND METHODS

Farm Experiment

The experiment, run over 3 yr (1998 to 2001) in the Waikato region of New Zealand, consisted of 5 herds, each grazed on its own farmlet. Stocking rates differed between the 5 farmlets: 2.2, 2.7, 3.2, 3.7, and 4.3 cows/ha (Macdonald et al., 2001). The aim was to quantify the change in efficiency of feed utilization and milk production when annual DMI per cow was altered through stocking rate. Because cow weights vary across farms in the New Zealand industry, stocking rate (cows/ha) was expressed as comparative stocking rate (**CSR**), defined as kilograms of liveweight (BW) per tonne of DM produced. By assuming an annual pasture production of 18 t of DM/ha, the CSR was set to 62, 76, 90, 103, and 120 kg of BW/t of DM for the 5 farmlets. Thirty-one hectares, already subdivided into 0.4-ha paddocks, were allocated to the trial. Five farmlets were established, balanced for geographic location, soil type, distance from milking parlor, and previous experimental treatments, such that farmlets were evenly spread over the farm in a checkerboard fashion. Herds consisted of 18 to 20 cows balanced for age, calving date, genetic merit, and BW. The farms were managed by policies called decision rules that have been described elsewhere (Macdonald and Penno, 1998). They include daily allowance of pasture and pasture silage, the area and timing of pasture conservation, and the timing of culling and drying off. Measurements used in the policies included net herbage accumulation, average herbage mass, pre- and postgrazing herbage mass (as kg of DM/ha), DMI, milksolids (**MS**, defined as fat plus protein), cow BCS, and BW. Trial measurements included pasture mass (by calibrated visual assessment weekly), pasture intake by difference between pre-and postgrazing assessed 3 d/wk, and pasture growth rate (**PGR**) calculated weekly from the increase in herbage mass on ungrazed paddocks (Macdonald et al., 2001). Milk weights and milk composition (fat, protein, and lactose) were determined on all cows weekly, and cow BW and BCS were assessed every 2 wk, immediately after morning milking.

WFM

Description. The WFM was developed to predict output relating to the whole farm (e.g., milk yield/ha per yr) and also to individual animals (e.g., milk composition) and paddocks (e.g., pasture yield/ha per yr). It was developed initially in VisualWorks Smalltalk 5i (Cincom Systems Inc., Cincinnati, OH) and then ported to VisualAge Smalltalk (IBM). Results were checked to be identical to simulations using VisualWorks. The WFM consists of a framework that links component models for animals, pastures, and crops (currently maize) as objects and these are retained in the language in which they were developed. New and revised component models can be added, keeping the system model flexible and up to date. Technical aspects of linking published models in different languages have been described (Sherlock and Bright, 1999).

The cow model "Molly" (Baldwin, 1995) runs in AcslXtreme (Aegis Technologies Group, Huntsville, AL) and has been modified for New Zealand animals by adding functions to account for weight gain during pregnancy, energy loss due to grazing, hormonal changes in older animals (Palliser et al., 2001), and photoperiod effects (Beukes et al., 2005b).

The pasture model is climate-driven and was developed in Fortran (McCall and Bishop-Hurley, 2003). Climate data from various regions throughout New Zealand consist of daily values for minimum and maximum temperature (°C), wind run (km), rainfall (mm), evapotranspiration (mm), solar radiation (MJ/m^2), and sunshine (h). Climate data are also used by some management policies; for example, when to remove animals temporarily from pasture, termed "standing-off." Economic inputs allow the user to determine the profitability as well as risk of any system. Risk is based on variations in climate, supplementary feed prices, and prices for milk and its components.

Use. The WFM software has user-friendly interfaces and runs stand-alone on a PC. The user sets up a simulation by indicating the length of the simulation (from days to multiple years), the climate data (region and year) to be used, the farm setup at the start date (animal and paddock characteristics), and management policies to be employed (described below). Cows are initialized to their genetic merit for milk production by using an industry-assigned factor called production value (Beukes et al., 2006).

Pasture quality is a user setting in WFM; it varies on a monthly basis using observed near infrared spectroscopy data from the experiment. Grazing selection was set arbitrarily at 100:55 for green:dead material in the sward; that is, all of the green matter will be consumed but only 55% of the dead matter. Pasture and feed supplement quality are divided into various components derived from the physical and chemical descriptions of the diet (Baldwin et al., 1987; Baldwin, 1995). Intake is calculated within Molly. When the cow is not lactating, the DMI is based on the energy requirements for maintenance, a function of metabolic BW, which is then divided by the ME of the feed to give DMI. When the cow is lactating an equation is used, based on >4,800 observations obtained in feeding trials in the United States (Brown et al., 1977; Baldwin, 1995), that is a function of DIM, the mature BW parameter in Molly, milk yield, and milk fat percentage. When the cow is pregnant the DMI calculations include the energy requirements of gravid uterus (i.e., conceptus plus uterus). Development of the fetus is based on published equations (Ferrell et al., 1976).

Model Simulations

Management policies were developed for the WFM. These included pasture feeding (rotation and postgrazing residual policy) and supplement feeding (type, amounts, and conditions for feeding), animals (timing and conditions for mating, drying off, once-a-day milking toward the end of the lactation, culling and replacements), and pastures (fertilizing in terms of amounts and timing, and conservation).The WFM was run using user-defined management policies that require certain conditions to be met before execution; for example, date(s), cow lactating or not, cow in-calf or not, cow certain BCS or not. Data from the first year of the experiment (1998) were used to develop these flexible management policies in WFM. Data from the other 2 yr (1999 and 2000) were used to set the model up for simulations; that is, develop the 5 farmlet scenarios, and then to compare model output with observed experimental results.

Each scenario was developed to simulate a year from June 1 to May 31 (the definition of a dairying season in New Zealand). At the start of a simulation, each cow (cow numbers varied from 18 to 20 depending on the treatment) was initialized by their age, BW, BCS, genetic merit using production value, last calving date, last mating date, and lactation and pregnancy status. The scenario also included 11 to 20 paddocks, each defined by their area and pasture cover on June 1. The WFM (version 1.1.5.d) then simulated daily output for each paddock and cow using management policies from the actual experiment and the observed climate data for that year. Substitution of pasture intake by supplementary feed was set at unity.

WFM Calculations

Predicted values for pasture and cow production were compared with observed values. Results including pasture growth rates and the feed intakes, milk production, and condition score of the animals. Body condition score was calculated in Molly by a function combining initial BCS with adipose tissue mass. It was converted from the US 5-point scale (US-BCS) to the NZ 10-point scale (NZ-BCS) using a variation of the equation of Roche et al. (2004);

$$\text{NZ-BCS} = 2 \times \text{US-BCS} - 0.5$$

Assumptions and Limitations

Among the assumptions made were that management policies were applied consistently in the trials (e.g., conservation occurred on proposed date), there were no cow health problems that affected production (e.g., mastitis), there was no topping of pasture (cutting with the purpose of removing poor-quality stalk), excess feed was conserved as silage, and cows were culled based only on performance or if they calved late relative to the rest of the herd.

Statistical Evaluation

The WFM-predicted results were compared on a monthly and annual basis with observed values of pasture cover, PGR, BW, BCS, milk yield, MS, and intake. The model predictions were compared with observed values using several statistical approaches as summarized by Shah and Murphy (2006). They included mean absolute error (**MAE**):

$$\text{MAE} = (\Sigma|O_i - P_i|)/n$$

where n is the number of pairs of observed (O) and predicted (P) values being compared, and the mean square prediction error (**MSPE**):

$$\text{MSPE} = \Sigma(O_i - P_i)^2/n.$$

Table 1. Annual results summarized for the 5 herds over 2 yr showing observed values and values predicted by the whole-farm model

Item[1]	Pasture cover (kg of DM/ha)	DIM	Annual MS[2] (kg/cow)	End BW[3] (kg)	Pasture production (kg of DM/ha)	Annual intake (kg of DM/cow)	
						Pasture	Total
Observed	2,220	260	346	489	18.8	4,815	5,066
SD Observed	168	29	58	25	3.2	691	712
Predicted	2,524	261	452	473	16.8	4,541	5,205
SD Predicted	197	29	47	18	1	536	335
Difference, %	14	0.4	31	–3	–11	–6	3
MSPE	110,342	12	11,564	843	9	143,555	170,088
RMSPE	332	4	108	29	3	379	412
MAE	304	3	106	24	2	306	345
RPE	0.14	0.01	0.31	0.05	0.12	0.06	0.07

[1]Difference, % = 100 × (predicted – observed)/observed; MSPE = mean square prediction error; RMSPE = square root of MSPE; MAE = mean absolute error; and RPE = relative prediction error.

[2]MS = Milksolids (fat + protein).

[3]BW = liveweight.

The square root of MSPE (**RMSPE**) is also known as the mean prediction error (**MPE**). The relative prediction error (**RPE**) was defined as the proportion of the observed mean values:

$$RPE = MAE/[\Sigma(O)/n]$$

For models of feed intakes, RPE values of <20% are considered accurate (Fuentes-Pila et al., 1996) and this criterion has been applied to evaluate the WFM predictions compared with observed data.

RESULTS

Results are presented in terms of animal and pasture production for the whole season (annual production) and across each season (monthly production) for all herds.

Annual Production

The results of comparing 2 years' production for the 5 herds are shown in Table 1. Observed and predicted values are shown with the difference expressed as a percentage, together with the statistical evaluation of the model predictions. Pasture covers at the end of the season differed by 14% from observed, and both covers and pasture production showed acceptable agreement of <20% RPE between the predicted and observed values. Predictions of pasture intake and total intake per cow were acceptable (<10% RPE; Table 1) and a plot of predicted vs. observed values for intake was close to unity (Figure 1). The mean prediction of end BW differed by only 3% from the mean of observed (Table 1 and Figure 2). Days in milk agreed with the observed (Table 1), but MS production was overpredicted by 31% (Table 1), and the amount was consistent (105 kg of MS/cow per yr) across all herds (Figure 3). A plot of residuals of pasture intake vs. MS showed that the overprediction of annual MS production was largely independent of the error in pasture intake prediction (Figure 4).

Monthly Production

Observed vs. predicted values for average monthly cover, PGR, MS, milk, BW, intake, and BCS are plotted

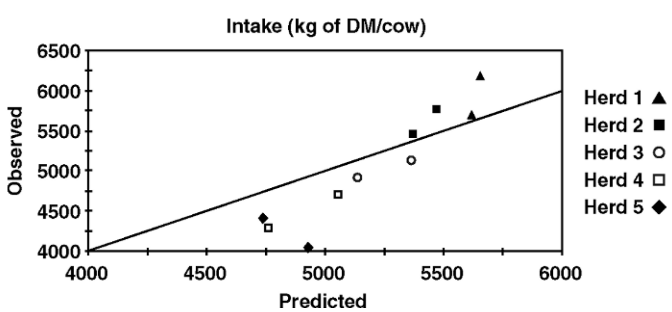

Figure 1. Intake (kg of DM/cow) for each of the 5 herds over 2 yr showing observed vs. predicted with unity line.

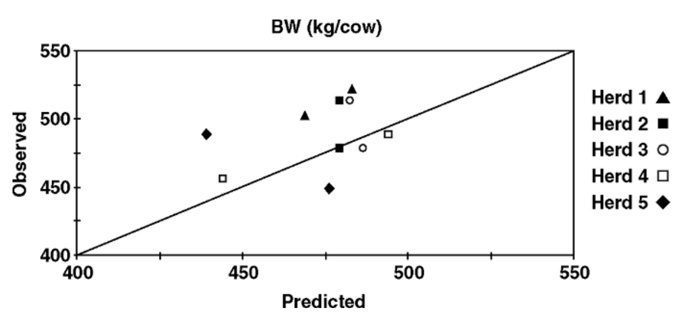

Figure 2. End of season cow liveweight (BW) for each of the 5 herds over 2 yr showing observed vs. predicted with unity line.

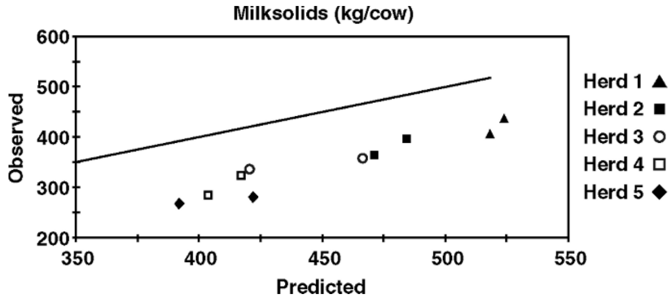

Figure 3. Milksolids (protein plus fat) for each of the 5 herds over 2 yr showing observed vs. predicted with the unity line.

for 1 representative herd (herd 3, 1999 season; Figure 5). There was close agreement between predicted and observed BW and BCS during the season and also for intakes and pasture cover but there were some differences between PGR and consistent differences between predicted and observed milk production data. These results were similar across all herds for both seasons (Table 2). The RPE of cover predictions were acceptable across all herds and all years with a mean RPE of 11%. Monthly PGR predictions had an average RPE >20%. There was overprediction in spring (mo 8) and fall (mo 3) and under prediction in late spring/early summer (mo 9 to 11; Figure 6). Predictions of pasture intake, total intake, BW, and BCS (Figure 7) were acceptable (average RPE <20%) for all herds over both years. Monthly average milk and MS production were overpredicted in all herds over both years (Table 2).

WFM Predictions vs. Trial Results

The WFM predicted that with increasing CSR, MS production per cow would decrease while MS production per ha increased (Figure 8), similar to the pattern of results from the actual trial (Macdonald et al., 2001).

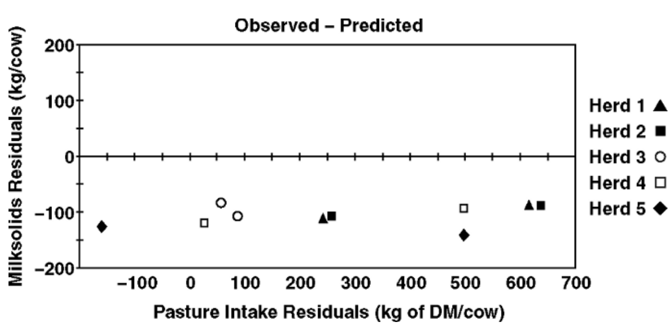

Figure 4. Residuals of annual pasture intake vs. milksolids for the 5 herds over 2 yr.

DISCUSSION

An evaluation of a WFM against animal and pasture data obtained over a 2-yr grazing trial showed that it can be used in evaluating some strategic and tactical management options for pasture-based dairy systems in the Waikato region of New Zealand. The model needs to be validated against observed data from other climatic regions and farm systems that include different levels of bought-in supplements, irrigation, cropping, split calving, and so on, before it can be used to explore management options on a wider scale. This exercise showed that the model has potential to give acceptable predictions of annual pasture production over 2 different climate seasons. It also predicted changes in pasture cover, BW, pasture, total feed intake, and BCS throughout the season for herds that were managed by the same rules but grazed at different stocking rates, and hence had differing management and feeding requirements.

Even though the intake predictions agreed with the observed values, milk and MS was overpredicted indicating that the metabolic cow model was too efficient in converting nutrients into milk. There are several reasons why the Molly model may be overpredicting milk production. The version used in these simulations has been shown to be insufficiently responsive to nutrition (i.e., milk energy output is too great on low energy diets; Hanigan et al., 2006). A refinement of the mammary model has been developed, called "Molly2006" (Hanigan et al., 2007). Second, an estimate has been included in Molly to account for energy expenditure due to walking and grazing; however, other energy costs such as thermoregulation may be underestimated. Third, because the overprediction occurs mainly in the summer period (October to December) in the southern hemisphere, it may be the result of a change in pasture quality. The less digestible summer pasture may have greater lignin and lower cellulose, hemicellulose, and protein levels than currently being captured in WFM (Holmes et al., 2002). A challenge is to interpret values from near infrared spectroscopy into feed fractions for Molly, and reinterpreting the composition of summer pasture may resolve this difference between observed and calculated milk production. Increasing lignin to 15% and concomitantly decreasing insoluble protein in the diet caused a decrease in modeled MS production similar to the observed data (data not shown). However, adjusting the lignin fraction also caused a decrease in cow BW prediction to below observed, lending weight to the hypothesis that the overprediction of milk production involved some aspect of metabolite partitioning.

Annual pasture production was predicted with an acceptable level of accuracy; however, monthly produc-

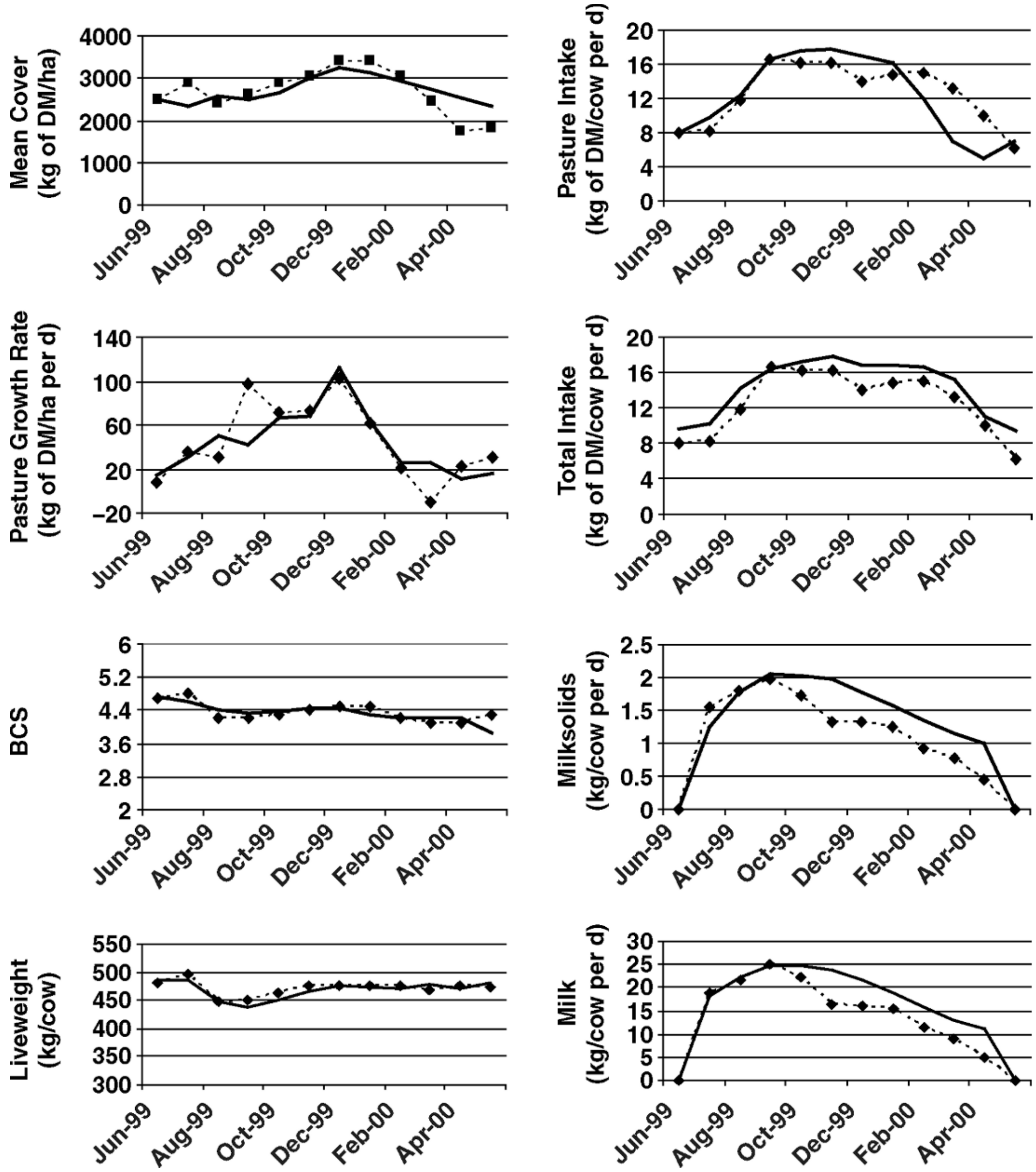

Figure 5. Results for herd 3 in the 1999 season showing monthly averages of observed data (dotted line with symbols) vs. predicted values (solid line).

tion was accurate during the slower growth periods (winter), underpredicted during the rapid growth periods of spring, and overpredicted during transition periods of late fall and early spring. Some of the difference between the predicted and observed PGR may relate to the frequency of measurement because observed values were made weekly, whereas in the model it was assessed by averaging the growth rate in all paddocks daily. The frequency of measurement affects the estimate of PGR (Prewer et al., 2002). Alternatively, the model may have allocated the feed more efficiently (e.g., grazed or conserved pastures at the optimal time) promoting greater growth rates (Jensen et al., 2005).

Because BCS was predicted with acceptable accuracy during the season, the WFM can be used to compare management strategies involving this measure, such as culling, mating, and drying-off. These are individual animal characteristics that could not be simulated if the cows were modeled as an average, or herd. Although not required for the current analysis, the WFM has the ability to model carryover effects where it may take several years for all the benefits to be realized; for exam-

Table 2. Relative prediction errors of animal and pasture results based on monthly averages for 5 herds over 2 yr

Herd[1]	Year	Cover[2]	PGR[3]	MS[4]	Milk	BW	Pasture intake	Total intake	BCS
1	1999	0.13	0.40	0.26	0.20	0.05	0.12	0.13	0.03
1	2000	0.12	0.25	0.23	0.16	0.05	0.14	0.06	0.03
2	1999	0.11	0.42	0.30	0.27	0.02	0.12	0.11	0.05
2	2000	0.10	0.28	0.25	0.22	0.03	0.16	0.08	0.06
3	1999	0.10	0.32	0.27	0.22	0.02	0.16	0.14	0.03
3	2000	0.09	0.32	0.30	0.25	0.05	0.15	0.14	0.03
4	1999	0.12	0.42	0.36	0.37	0.03	0.14	0.20	0.03
4	2000	0.12	0.41	0.25	0.26	0.04	0.22	0.19	0.03
5	1999	0.14	0.51	0.45	0.40	0.03	0.18	0.36	0.03
5	2000	0.11	0.35	0.52	0.36	0.10	0.19	0.17	0.06
Mean		0.11	0.37	0.32	0.27	0.04	0.16	0.16	0.04
SD		0.02	0.08	0.10	0.08	0.02	0.03	0.08	0.01

[1]Herds 1, 2, 3, 4, and 5 had stocking rates of 2.2, 2.7, 3.2, 3.7, and 4.3 cows/ha and comparative stocking rates of 62, 76, 90, 103, and 120 kg of BW/t of DM, respectively.

[2]Pasture cover.

[3]Pasture growth rate.

[4]Milksolids (fat plus protein).

ple, improving the reproductive performance of a herd (Beukes et al., 2005a). Future development of the WFM will include updating Molly to Molly2006 (Hanigan et al., 2007), adding crop models other than maize, labor accounting, and synthesized climates, where the user can mix and match seasons (e.g., a wet, cold spring with a hot, dry summer) for their region.

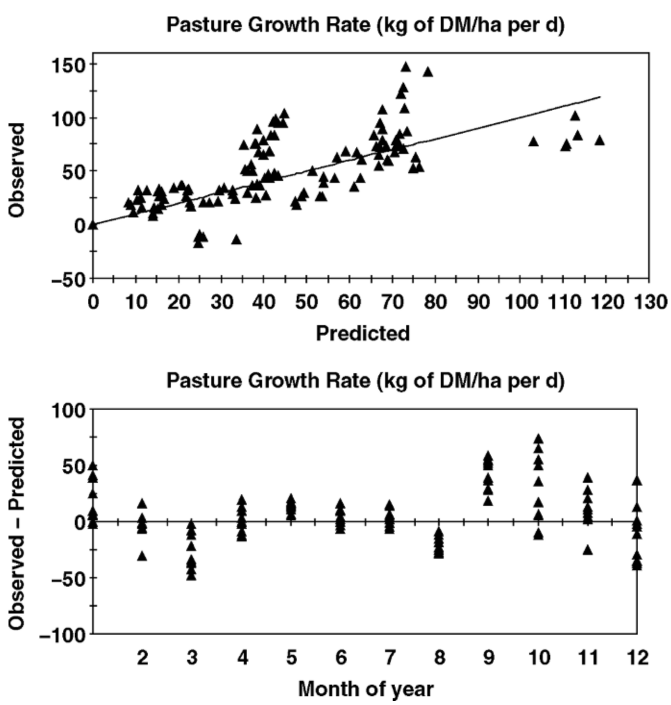

Figure 6. Pasture growth rate averaged by month for the 5 herds over 2 yr showing observed vs. predicted with unity line (upper), and residuals vs. month (lower; 1 = Jan etc.).

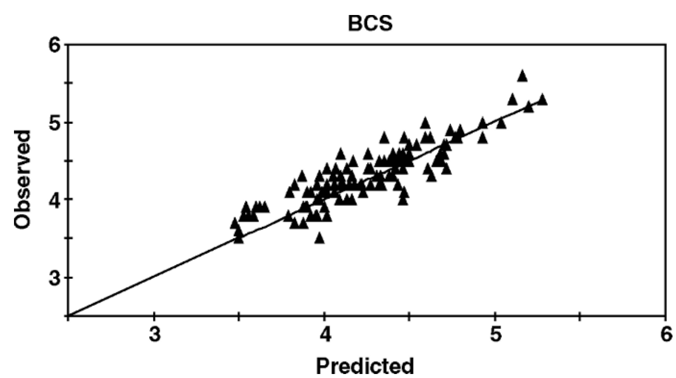

Figure 7. Body condition score averaged by month for the 5 herds over 2 yr showing observed vs. predicted with unity line.

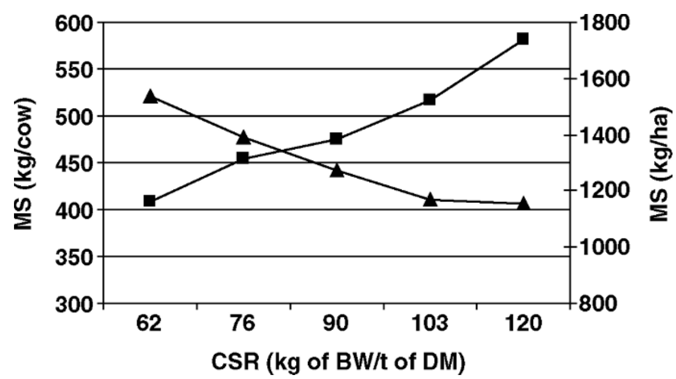

Figure 8. Predicted milksolids (MS, protein plus fat) per cow (diamonds) and per hectare (squares) vs. comparative stocking rate (CSR).

In conclusion, a whole-farm model using published mechanistic models for pasture growth and cow metabolism has been evaluated against trial data by applying the same management policies as in the actual trial. Results showed that the model has acceptable accuracy for pasture and cow predictions relating to BCS and BW but a constant is required to adjust for milk production until the cow model is further refined. With this accounting, the WFM can be used to compare management strategies and economics for a range of pastoral systems for both research trial design and for actual farms.

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