Modelling the Lactation Curves of New Zealand Cows

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Abstract The development of a computer model of a pasture-based, rotationally grazed dairy farm is important for the planning of farm systems trials in New Zealand. It will enable researchers to simulate different trials and select the most productive scenarios for testing on-farm. Dexcel, a dairy research company, is developing such a computer model, known as a Whole Farm Model (WFM). It includes component models for cow metabolism and pasture growth, as well as climate and management information. Papers describing the WFM have been presented at previous MODSIM conferences. These papers have provided an overview of the WFM, particularly in relation to the way object-oriented programming has been used to facilitate the incorporation of the component models. This paper focuses on one of these component models, namely the cow model called MOLLY, and its simulation within the WFM. MOLLY is a dynamic model with over 1000 parameters representing the processes of ruminant digestion and metabolism. The parameters of MOLLY are based on a cow fed high-energy rations whereas the primary feed source of a New Zealand cow is pasture. This paper describes the adjustment of selected parameters within MOLLY that lead to predicted seasonal lactation curves that fit experimental observations. This refinement will enable MOLLY to be more useful as a research tool to gain insights into changes in metabolism of cows when grazed on pasture, and to predict effects on production when changes are introduced in farm systems practice.

Keywords: Computer model; Cow; Milk yield; MOLLY

1. INTRODUCTION

The Whole Farm Model (WFM) has been developed at Dexcel over the last 5 years. It is a complex computer model that can model events that happen on a dairy farm at an individual paddock and cow level on a daily basis. It consists of a framework called the Farm System Simulation Framework (FSSF) to which are attached component models for pasture growth and cow metabolism. Also included in the WFM are climate and management information. Some of the developmental and computing aspects of the WFM have been described at previous MODSIM conferences [Neil et al., 1997; Sherlock et al., 1997; Sherlock and Bright, 1999], and also at a Complex Systems conference [Bright et al., 2000].

There are 3 cow models to choose from when using the WFM, the most complex one being MOLLY [Baldwin, 1995]. It is a mechanistic dynamic model based on a cow's metabolism that is parameterised for a cow fed high-energy rations. Palliser et al. [2001] noted that MOLLY required further adjustment in order for there to be a better fit between a New Zealand cow's observed and predicted milk yields. This paper is the next step in this adjustment process, i.e. a parameter is adjusted in MOLLY so that her milk yield values (or lactation curve) better fits the observed milk production data from groups or herds of New Zealand cows.

Previous analysis of milk production from animals has mainly been done by using empirical methods of fitting curves to the data. The most commonly used curve is that described by the gamma equation proposed by Wood [1967]. Other empirical models exist, see Neal and Thornley [1983], Rook et al. [1993] and Dijkstra et al. [1997] for references and/or some discussion of these. As noted by Dijkstra et al. [1997] and Pollott [2000], the parameters of the lactation curves described by these empirical equations often have little or no biological meaning. Hence they provide limited insight as to what is happening to the animal during lactation. This paper will therefore discuss mechanistic models.

2. BACKGROUND

There are basically 2 types of mechanistic mammary models for dairy cows: (i) those that describe and model its metabolism, see for example Hanigan and Baldwin [1994] and Cant and McBride [1995] and, (ii) those that model milk production in relation to the development and decline of mammary gland cells and the secretion of milk. In this paper we are primarily interested in the type (ii) models.

Pollott [2000] summarised the research into the change in cell numbers in the mammary gland during pregnancy and lactation. Three major processes are involved: mammary parenchyma cell proliferation, their differentiation into cells showing secretory activity and the reduction in their numbers due to cell death. Cell proliferation starts in early gestation and rises exponentially until it reaches its maximum just after parturition. Cell numbers start to decline at or soon after parturition, and this decline continues throughout lactation. The number of cells present at a particular time is given by the net effect of cell proliferation and death. With regard to the secretion rate of the differentiated cells, Pollott said that current research, limited as it is in this area, shows that there appears to be little variation in the secretion rate per cell over a lactation for a given milking regime. Pollott concluded that milk production during early lactation is mostly due to the rate at which cells become active or differentiated, and the decline in milk yield later in lactation is due to the rate of cell death.

2.1 A Brief Review of Mechanistic Mammary Gland Models

Neal and Thornley [1983] represented the mammary gland as undifferentiated cells, which differentiate or divide to give secretory cells. The differentiated secretory cells die after a certain length of time at specific rate. This rate will increase due to biochemical and physical pressures if the milk is not removed from the cow over a period of time. The secretion rate of milk was assumed to be proportional to the number of secretory cells and is inhibited if the amount of milk approaches the maximum capacity of the cow. Their model's fit to observed milk yield from lactating cows was good and they altered some of the model's parameters in order to model different milking regimes.

Dijkstra et al's [1997] mammary model consists of a pool which is the cell population of mammary tissue, an influx – cell proliferation, and efflux – cell death. They assumed that after parturition, the rate of cell proliferation declines exponentially with time and the rate of cell death is constant. In order to use their model for milk production, they introduced a term for mean milk production per secretory cell per day. Dijkstra et al. [1997] compared the predicted milk yield from their model and also that of Wood's [1967] empirical model with data observed from 23 animals fed a variety of diets. They observed that in general their model fitted the data better than that of Wood's.

Pollott [2000] developed a mechanistic model for daily milk yield based on the number of active or secretory cells and their secretory rates. This number of secretory cells is the difference between the number of differentiated cells produced and the number dying off. Both of these numbers were calculated from logistic curves with respect to time. Pollott's model can be adapted to account for an improvement in nutrition on milk yield by allowing for a second growth of secretory cells followed by a new rate of cell death at the time of the nutrition improvement. Pollott also could increase the rate of cell death after conception by assuming that pregnancy increases the rate of loss in milk secretion potential. Pollott's model(s) compared well with some observed data from dairy cows and fitted the observed data better than other models of the lactation curve, including those of Wood [1967] and Dijkstra et al. [1997]. Pollott identified secretory cell death as a key feature of lactation.

Davis et al. [2001] represented the mammary gland as 2 types or pools of secretory cells, some actively secreting whilst others were quiescent. The milk yield was not only a function of the active secreting cells, but also of the energy status of the lactating cow. They used their model to investigate the effect of nutrition on different genotypes.

3. METHOD

MOLLY uses Neal and Thornley's [1983] mechanistic model of a mammary gland in order to calculate milk production. MOLLY calculates milk yield as a function of udder lactose which depends on mammary gland model parameters and the concentration of glucose and acetate in the blood. In MOLLY the blood glucose and acetate vary according to the cow's nutritional status, so MOLLY's calculation of milk yield accounts for nutritional effects on milk production. Being able to include nutritional effects on milk yield makes the mammary model within MOLLY a powerful tool and it is something that Neal and Thornley [1983] acknowledged as a major developmental difficulty. We will not be concentrating on these nutritional or metabolic aspects of milk production here, but rather looking at the mammary gland model parameters.

For New Zealand pasture-fed cows, milk production peaks in a matter of a few weeks from calving (commencement of lactation) and then reduces as the season progresses and eventually stops in April/May when the cows are dried off. In New Zealand, the period of greatest pasture growth and hence most availability of feed for the cows coincides with the period of peak lactation or milk yield.

The cows (n = 14) used in this paper are taken from one of the herds that were participating in a stocking rate trial during the 1998 –1999 season at Dexcel (formerly Dairying Research Corporation) situated in Hamilton, New Zealand, Macdonald et al. [2001]. Figure 1 compares the predicted lactation curve for a typical young cow (≤ 2 years of age) with the observed milk yield. The lactation curve fits the data well.

Figure 2 shows predicted and observed milk production for an older cow (> 2 years). In this figure, the lactation curve decays too slowly after the peak. This occurs for all the older cows in our herd of 14 animals, but for the younger cows (Figure 1), the decay is about right. This suggests that this decay rate is age-related.

In Neal and Thornley's [1983] model the decay rate depends on the number of secretory cells being produced versus those that are dying off. In order to correct the decay rate for the older cows it was proposed to decrease the rate at which the differentiated secretory cells are being produced. This production (P) is given by Neal and Thornley [1983] in terms of a Michaelis-Menten type equation:

$$P = v_{max}\left(\frac{1}{1 + K_M / H}\right)C_u \qquad (1)$$

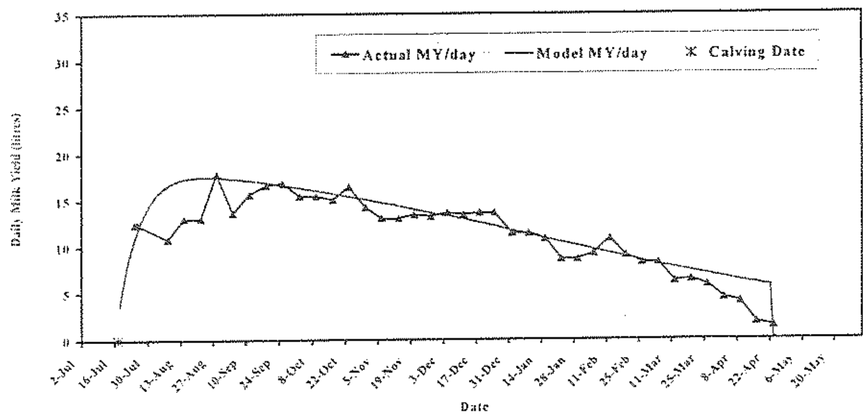

Figure 1. Predicted (model) and observed daily milk yields (litres) of a typical young cow ($\leq$ 2 years of age).

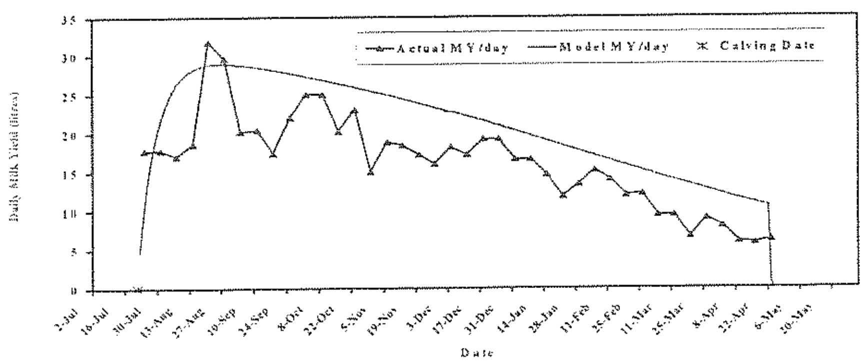

Figure 2. Predicted (model) and observed daily milk yields (litres) of a typical older cow (> 2 years of age). k_H constant for all cows = 0.0102 per day.

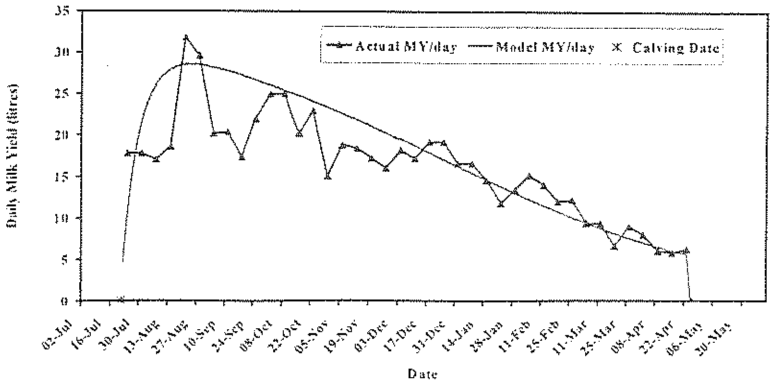

Figure 3. Predicted (model) and observed daily milk yields (litres) of the same older cow as in Figure 2. $k_H = 0.0132$ since cow is 5.91 years old.

where v_{max} is the maximum velocity or response (divisions/cell/day), K_M is the Michaelis-Menten constant giving half-maximal hormone response (kg/m^3), C_u is the number of undifferentiated cells, and H (kg/m^3) represents the concentration of hormones which initiate lactation. K_M and v_{max} are constants and C_u is assumed to be constant. Decreasing H in Equation (1) results in a decrease in P. Neal and Thornley [1983] assumed that H decays exponentially with rate constant k_H = 0.0102 per day, and they solved the differential equation for H to obtain:

$$H = H_0 \exp(-k_H t) \qquad (2)$$

where H_o is the concentration of H at time t = 0. In order to decrease H for the older cows, it was decided to increase their k_H as follows:

k_H = 0.0132/day for cows ≥ 4 years of age, an increase of 29%;

k_H = 0.0112/day for cows between 2 and 4 years of age, an increase of 10%;

k_H remains unchanged at 0.0102/day for cows ≤ 2 years of age.

4. RESULTS

Figure 3 shows the same cow as that shown in Figure 2 (k_H = 0.0102), but in Figure 3, k_H has been adjusted to 0.0132 since this cow is 5.91 years old. From about January onwards, the lactation curve predicted by the model in Figure 3 is a better fit to the observed milk yield than the curve in Figure 2, i.e. Figure 3's lactation curve decays more appropriately in mid to late lactation than Figure 2's.

We calculated:

(i) the mean absolute difference between predicted (model) and observed (actual) milk yield (litres/day) for the herd (n=14) and,

(ii) mean absolute percentage error for the herd given by the following formula:

Error = |100(PMY – OMY)/OMY|

where PMY and OMY are predicted and observed milk yields respectively. Table 1 summarises the results of these calculations.

Table 1. The means and standard deviations of the absolute differences (Diff) and errors (Err) for k_H constant and k_H adjusted according to cow age, with the percentage improvement (% Impr) in fit obtained using the adjusted k_H.

		k_H constant	k_H adjusted	% Impr
Whole curve	Diff	2.91 (1.35)	2.22 (0.74)	24
	Err	25.06 (11.49)	17.82 (7.71)	29
January onward	Diff	2.89 (1.89)	1.76 (1.15)	39

The 'Whole curve' in Table 1 refers to the whole lactation period, from commencement of lactation until dry-off. 'January onward' is the latter part of the lactation period (from January onwards). The fit obtained by adjusting k_H shows a greater improvement for 'January onward' than that for the whole lactation period – 39% improvement versus 24% respectively.

5. DISCUSSION AND CONCLUSION

Other researchers have noted that a cow's milk yield varies with age. Bywater [1976] developed an empirical simulation model for dairy cows which predicted milk yield. He noted that cows have differences in their lactation curves depending on their age or more specifically on which lactation they are in (for example, if this is the second time a cow has calved and is lactating, then this is her second lactation). For the purposes of his model he used three classes, namely first, second and subsequent lactations, each of which had different secretion rates. Pollott [2000] stated that the number of mammary parenchyma cells increases between the second and third lactations, but information regarding further lactations was unavailable. Therefore varying k_H with age as we have done in order to change the decay rate of post-peak milk production and hence the shape of the lactation curve, is consistent with the findings of these other researchers, i.e. that a cow's milk yield varies with age.

Currently MOLLY is fed different amounts of pasture according to her nutritional needs, but the components or chemical composition of this pasture remains unchanged even though pasture composition and quality vary during lactation. Baldwin [1995] demonstrated the big effect that different components have on the shape of the lactation curve as predicted by MOLLY. Therefore it is postulated that once MOLLY's dietary components are varied based on seasonal differences, then the observed milk yields may be even better modelled.

As MOLLY becomes better parameterised for a New Zealand pasture-fed cow, the WFM will become a powerful research tool, enabling scientists to investigate, for example, the variation of milk production and methane emission rates with diet. Using the WFM to experiment like this will reduce the number of farm trials required and hence save time and money. For MOLLY to be a better model for a New Zealand cow, additional experimental work may be required, i.e. improvements required by the WFM will drive farm research.

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