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Development and validation of a mechanistic whole dairy farm model to evaluate farming strategies under grazing conditions in Uruguay.

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Abstract: A mechanistic, dynamic whole farm simulation model was developed to evaluate the effect of farming strategies on the productivity of dairy grazing systems. The model integrates local available information on pasture growth and quality and current knowledge on animal nutrition and metabolism. The pastoral component simulates the pasture rotation structure of the farm, with variable number and size of paddocks, to which the user must assign a pasture type from an available database. Each pasture type is represented by initial herbage mass (**HM**) and two vectors: monthly dry matter (**DM**) growth rate values and organic matter digestibility (**OMD**) values. The model is driven by pasture growth rate (**PGR**) on a monthly interval step. Several pasture production and management strategies can be defined as a per paddock basis. The cows are defined in terms of their potential for milk production (**MPP**), body condition score (**BCS,** scale 1-5), biotype **Frame** (body weight with BCS of 3), calving date, and contents of fat and protein in milk. These variables are used to characterize the average of up to six groups of adult cows which are defined by the user to represent the current situation of a dairy farm or a theoretical system.

Average grazing **DM** intake (**DMI**) of each calving group of cows is estimated considering animal factors: **Frame**, **MPP** and days in milk (**DIM**); pasture factors: **OMD,** pre-grazing **HM** (**pg-HM**) and substitution rate (**SR**) of supplementary feed. The model is based on metabolisable energy (**ME**) and environmental thermo neutrality is assumed. Total **ME** intake (**MEI**) is partitioned among body functions following a defined priority: maintenance, pregnancy, milk production potential and body reserves (**BR**). One distinct feature of this model is that the approach used implies an active role of **BR** in defining the partition of **MEI**. If **ME** balance for potential milk is not achieved then **BR** are mobilized at a constant rate (**κ**) to give an absolute amount which is proportional to the current size of estimated mass of **BR**, whose initial level is set when inputting the initial **BCS**. Another feature of this model is that it can manage decisions taken at different system levels (pasture rotation structure, annual **DM** yield and seasonal distribution, reserves production and supplementation strategies, variables stocking rates, effects of animal size, **BCS**, milk potential, etc.), to quantitatively assess the impact of these decisions on cows and farm productivity.

The model output was initially validated at the "cow biotype level" using published farmlet trials. The relative prediction error (**RPE**) and concordance correlation coefficient (**CCC**) were used as measures of fitness; models with values of **RPE** less than 10% and values of **CCC** greater than 0.90 were considered to have significant predictive power. Daily milk yield per cow, live weight and **BCS** change through the lactation were validated using a set of 12 monthly values for each trait, obtained from cows of contrasting body sizes (**Heavy** and **Light**).The **RPE** and **CCC** were 16% and 0.94 in **Heavy**, 20 % and 0.87 in **Light** cows for milk yield; 3 % and 0.72 in **Heavy**, 2 % and 0.81 in **Light** cows for live weight; 6 % and 0.18 in **Heavy** and 9% and -0.47 in **Light** cows for **BCS** change.

Monthly intake of pasture per ha was validated using another independent set of 12 average monthly values for each of 5 farmlet stocking rates treatments (2.2; 2.7; 3.1; 3.7 and 4.3 cows/ha). **RPE** and **CCC** were: 13% and 0.77; 9% and 0.87; 12% and 0.93; 13 % and 0.91; 16 % and 0.88 respectively. The model was responsive to contrasting cow type and farming management. These results show that the model has acceptable predictive power and can be used to better understand actual farming systems and also to evaluate the expected productive impact of some technical changes introduced at the farm level.

Keywords: *Farm model, Farming systems, Grazing model, Dairy cow model*

1. INTRODUCTION

In Uruguay cows are maintained outdoors all the year round grazing a variety of mixed legumes/grass swards and annual forage crops, which are sown in sequence over time, generating the so called pasture rotations. Over 90% of the national dairy herd is based on the Uruguayan Holstein breed, mostly originated from North American Holstein type of cattle. Results from the National Genetic Evaluation show that average milk production per cow varies from 3000 to over 7200 kg /305-day lactation with autumn and winter as predominant calving season (Ravagnolo, O., Personal Communication). A recent study also showed large variability of farming systems (Nozar, 2006); stocking rates varied between 0.4 to 1.2 adult cows per hectare and conserved forages and concentrates accounted for 10 to 50% of the expected total dry matter intake of the milking cows.

This variability in production systems is associated with different pasture rotations and agronomic practices that lead to variable seasonal and annual DM yields, which are also coupled with several pasture conservation and supplementation strategies, stocking rates, calving pattern, cow biotype, etc. This complexity makes it very difficult to quantitatively assess feeding and management decisions for grazing dairy cows and hence farm productivity.

Currently there are no practical computer tools in Uruguay that integrates dairy cows feeding knowledge with local available information on pasture production and farming practices. Therefore it was decided to develop a mechanistic whole dairy farm model based on earlier modeling efforts (Durán, 1983), using updated knowledge on animal nutrition and the potential of rapid application development languages.

The model can accommodate local and general knowledge on milk production with the aim of better understanding actual farming systems and to facilitate quantitative evaluations of alternative production strategies.

The objective of this paper is to present an overview of the model and to discuss its initial evaluations.

2. MODEL OVERVIEW

The model was written using Visual Basic computer language (Microsoft® Visual Basic® Professional, 2005) and comprises a set of interactive forms prompting the user to input the basic information that characterize an actual dairy farm or a theoretical production system. The initial data and outputs of each farm and farming scenarios can be saved and easily recovered for further use. All relevant information is stored using MySQL® open source database.

Representation of pasture management of the dairy farm is defined at the paddock level while herd productivity is defined at the cow level. The model represents the total farm area of the farm where the pasture rotation system and conservation practices are implemented. This area is assumed to be used by a stable milking herd with a variable number of groups of cows calving at different times throughout the year. Replacement animals are not considered in the model.

The model simulates annually from March of each year, with a time step of one month. All time dependent variables are estimated on a daily basis and extrapolated to obtain the corresponding monthly total and mean values. Each calving group maintains its own days in milk (**DIM**) to correctly manage all the events of the calving cycle.

The simulation of the grazing management for each paddock accommodates one milking herd and another of dry cows. Each calving group is automatically moved in or out the milking or dry herd as calving or drying off takes place.

A variable number of individual paddocks can be defined, to which the user must input its area (ha) and assign a pasture type that is selected from a displayable list. Once a pasture type has been selected, the model loads two vectors from a database, one with the information on monthly pasture growth rate (**PGR**) and the other with the monthly average value for organic matter digestibility (**OMD**). There are over seventy different local pasture options available to select for an individual paddock. The user must also select some basic decisions rules. For example, minimum residual herbage mass (**HM**) after grazing, whether the paddock will be used only by milking, dry or alternatively by both types of cows. If the paddock is intended for conservation the user must enter the closing date, the HM at harvest and the residual after cutting.

Except where otherwise mentioned, the equations used are the same as described in the initial version of the model by Duran (1983) and are also available on request from the corresponding author.

2.1 Definition of Cow Attributes

Each group of cows is defined by an average calving date, the number of animals and a set of attributes selected to define the type of the cows. For the practical purpose of the model, the average cow type is defined by four main attributes: (1) the **Frame** as a reference to the size of the cows; (2) the average body condition score (**BCS)** (1-5 scale) (3) The expected milk production potential (**MPP),** and (4) milk solids composition (%) in terms of fat (**F**) and protein (**P**). For most intake prediction equations, body weight (**BW**) has been used as a proxy for size (Forbes, 1988; Shah and Murphy, 2006) but due to large variation in **BW** associated with changes in body reserves (**BR),** the BW must be related to a standard BCS**.** Therefore the inputted Frame of the cows is represented by the BW of an empty cow with a BCS of 3.The user must enter an initial BCS. The absolute amount of BR is estimated as suggested by NRC (2001) from Frame and BCS.

The MPP represents the phenotypic milk yield potential of a given herd (kg of milk/cow/year), if the cows were given unrestricted amount of high quality feed. Daily MPP is derived using a gamma function (Wood, 1967) that represents a typical lactation curve (expressed as multiplicative factor) with peak milk yield in week 6 after calving. The initial absolute MPP value must be entered by the user and will be the same throughout the simulated scenario, except that daily MPP values for the first two month of lactation were not achieved. In this case the MPP for the whole lactation will be affected by a negative residual effect amounting 250 L/lactation for each kg of milk not produced below the initial MPP (Broster and Broster, 1984).

The reproduction events are driven by the mean inter-calving period (**ICP**) of the herd. A ICP greater than 365 days means that a proportion of cows will not be calving within the simulated year. These cows have to be assigned by the user to a calving group nominated as "0". This group is assumed to calve before the beginning of the simulated year and their initial DIM is given by (ICP-365)/2. It is also assumed that all cows become pregnant 280 days before the expected calving date of the group.

The underlying assumptions of this approach is that the main productive differences between contrasting cow types are essentially related to cow size, milk yield, total DMI and the amount and extension of BR partitioned to milk during the lactation cycle. This has been demonstrated from previous grazing experiments with genetically diverse dairy cows (Holmes, 1988; Dillon et al., 2006; Roche et al., 2006) and confirmed by detailed calorimetric studies (Yan et al., 2005) which did not demonstrate any difference in the partial efficiencies of metabolizable energy (**ME**) use for milk secretion by completely different cows genotypes.

2.2 Feeding Strategies

The model allows the user to define specific supplementary feeding strategies for each group of cows. The type of supplement is chosen from a displayable list with the user also defining the daily amount on a per cow basis must be defined. Supplements can be assigned independently to each one of four conventional stages of the lactation. It is assumed that the daily amount of supplement is completely eaten.

2.3 Intake Module

Total dry matter intake (**TDMI**) of each calving group is estimated considering pasture factors (OMD, pg-HM), animal factors (Frame, MPP and DIM); and supplementary feed (daily amount, substitution rate (**SR**)). The effect of OMD on intake is calculated using a linear relationship between pasture DMI (g/kg BW) and OMD (%)**,** which is scaled to a cow producing 5000 L/lactation (Duran, 1983). Frame (kg) works a**s** a multiplicative factor to estimate a mean DMI**.** This mean value is increased or decreased as MPP departs from 5000 L, on the basis of 0.25 kg DMI per L of milk (Mayne and Wright, 1988). The effect of the stage of lactation on the potential pasture DMI **(PP-DMI)** is determined by DIM

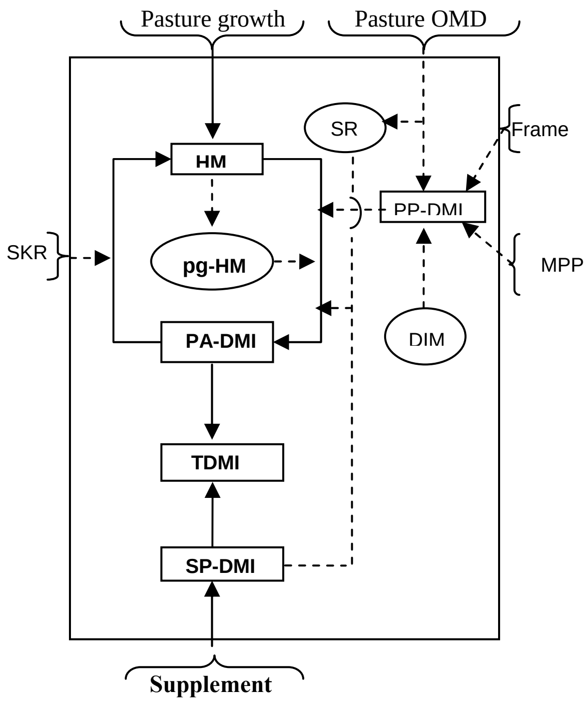

Figure 1 Representation of the intake module.

Inside the limits, solid line represents materials fluxes, slashed lines are information fluxes.

using a gamma function to describe a typical daily DMI pattern (expressed as a multiplicative factor) over the lactation with maximum intake at week 16 of lactation. Figure 1 represents the relationships among these components used in the model. The feeding value of the pasture is represented by OMD which also affects the SR. The level of cow's PP-DMI is estimated considering first the OMD of the grazed pasture and then the animal factors as mentioned above. The actual pasture DMI (**PA-DMI**) is the result of the restrictive effects on PP-DMI of pg-HM and the corresponding effect of the SR and the amount of supplements fed. Total dry matter intake (TDMI) is the sum of the PA-DMI and the amount of supplement DMI (**SP-DMI)** fed. Therefore, actual TDMI is estimated independently of actual milk yield and body weight changes, which are estimated from the estimated ME energy intake (**MEI**) and its partition to different body functions as outlined in the energy partition module. PA-DMI is converted to MEI using OMD as suggested by AFRC (1993).

2.4 Energy Partition Module

Energy requirements are estimated under the assumption that animals are in a thermo-neutral environment. This module performs the partition of the estimated MEI into body functions assuming that daily MEI is used for a particular function in a priority order. Oldham and Emmans (1989) suggested the priority order in cattle is (1) maintenance of essential metabolic processes, (2) pregnancy, (3) lactation, (4) growth to ensure target body weight at maturity and (5) body fat accretion or depletion to achieve metabolic target BR mass. The daily ME requirement for maintenance, milk production, live weight change and gravid uterus (**GU**) development were calculated following AFRC (1993), including the partial efficiencies of ME use. The net energy maintenance requirement proposed by AFRC (1993) is increased by 30 % as discussed by Agnew and Yan (2005). The energy cost of grazing is estimated taking into account the BW of the cows and HM as proposed by Duran, (1983). Daily BW change (**BWC**) includes BR variations plus the weight of the corresponding GU if cows are pregnant. The essential components of the model and their interactions are shown in Figure 2. The key factors were the identification of the BR mass as a separate entity of cow BW and also defining its daily maximum mobilization rate (**DMBRM**) as a proportion of its total amount. The amount for DMBRM is calculated using a rate constant (**κ**) as suggested by Duran (1983). Thus the residual ME intake (**RMEI**) obtained after accounting for the energy expenditure for maintenance, grazing and pregnancy, is assumed to be used with priority to satisfy the energy demand of daily MPP**.** If the RMEI is in excess of the MPP then actual milk yield equals MPP and the remaining RMEI is directed to accrue BR. If RMEI is not enough to fulfill the MPP requirement, then BR are mobilized to cover the deficit, but within the limit imposed by the DMBRM. If the DMBRM is not enough to achieve the MPP, then the actual milk yield will be lower than MPP and the loss of BR (and BCS) will be the maximum allowed by the absolute value of the actual BR and the rate constant **κ**.

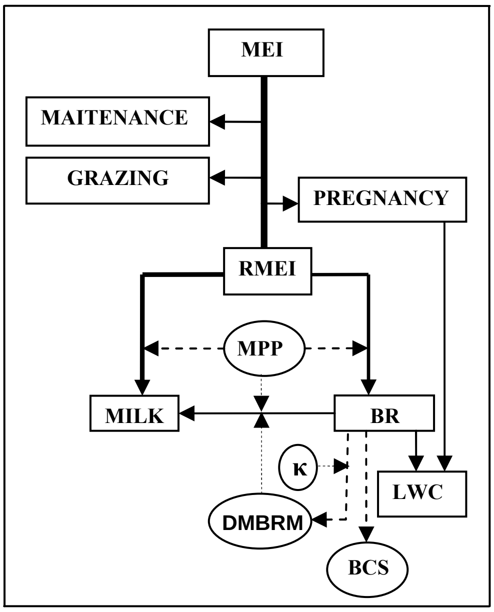

Figure 2 Representation of energy partition.

The BW change (BWC) depends on the balance between changes in BR and the actual growth of the gravid uterus. Negative (positive) changes in BR always imply a loss (gain) in BCS but BWC will not necessarily be negative, as it can be offset by a similar or greater increase of GU**.**

The homeostatic and homeorhetics controls of energy partition (Bauman, 2000; Friggen and NewBold, 2007) used in this model are represented by the constant rate **κ** and two variables dependent on time (PP-DMI and MPP per day). These controls operate so that they only set the reference limits within which the actual cow variable output (milk**,** BR) is freely determined by the environmental factors that influence MEI.

2.5 Pasture Management Module

This module simulates the monthly pasture growth and the herbage mass of the farm area based on the decision rules selected at each individual paddock. The HM of each paddock at the beginning of the next month is calculated as: $HM_{(t+1)} = HM_{(t)} - (PA\text{-}DMI * SKR)_{(t)} + PGR_{(t)}$, where **SKR** is the average stocking rate on each paddock, and PA-DMI is the average intake of the calving groups of cows grazing together in the corresponding month.

3. MODEL USE AND VALIDATION

The model produces a number of outputs. Pasture growth, pasture harvested by cows or cuttings per ha and HM before and after grazing are estimated monthly for each paddock and averages of the whole farm are presented. Monthly averages for each calving group of cows include: DM and ME intake, daily milk yields, BW and BCS. Aggregated monthly and annual reports per farm, cow or paddock can be produced to fit user requirements.

3.1 Model Evaluation

Data were obtained from two published farmlet experiments that provided adequate information to test the model. The study by Lopez-Villalobos et al. (2001) was used to validate the ability of the model to represent different genotypes of cows. They compared daily milk yield, BW and BCS change through the lactation of two lines of cows with contrasting average size (Heavy = 517 kg vs. Light = 453 kg) but similar breeding values for milk solids production. The experiment by MacDonald et al. (2008) was used to validate pasture intake prediction by the model. They studied five stocking rates using balanced groups of cows of the same breed and presented the monthly evolution of the mean estimated intake per cow and per ha. Typical New Zealand annual pasture growth rate and OMD curves (Holmes et al., 2007) were used to distribute monthly the annual pasture DM informed in each experiment.

Fitness of the model was determined using the Relative Prediction Error (**RPE**) and the Concordance Correlation Coefficient (**CCC**). RPE was calculated as: RPE = MPE / $\overline{A}$, where Mean Prediction Error (**MPE**) = $\sqrt{MSEP}$ and Mean square error of prediction (**MSEP**) $= \frac{1}{n}\sum_{i=1}^{n}(A_i - P_i)^2$. CCC was calculated as:

$$CCC = \frac{2S_{AP}}{S_A^2 + S_P^2 + (\overline{A} - \overline{P})^2}$$

where Ai is the ith observed value and Pi is the ith predicted value by the model. Means, variances, standard deviations and covariances of Ai and Pi were calculated in the usual way.

3.2 Results and Discussion

Figure 3 shows the actual and predicted values for daily milk yield, BW and BCS of light and heavy cows. Table1 shows the average cow data for eight month of lactation together with the annual average of pasture DMI for each individual stocking rate and the corresponding model fitness parameters for both sets of data.

The shapes of actual and simulated lactation curves were similar but daily milk yield was under predicted in the first two months of lactation. After peak milk yield, the agreement between actual and predicted values was satisfactory. The RPE values (Table 1) were acceptable, with values between 16 and 20 %.

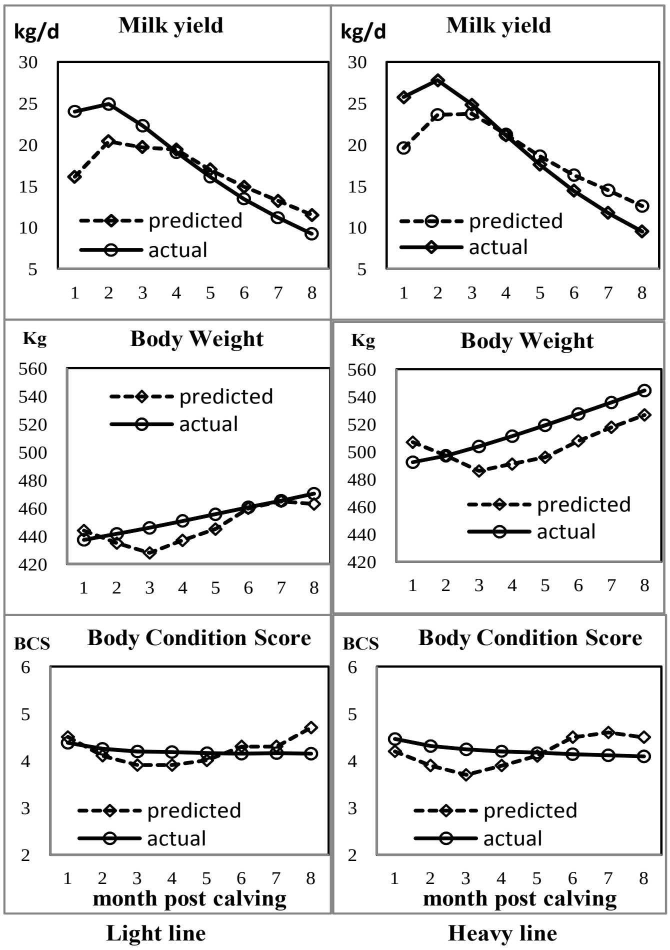

Figure 3. Results of light and heavy lines of cows showing monthly averages for actual and predicted values.

Table 1. Actual and predicted values for animal output and pasture intake based on monthly averages of two lines of cow and five stockingrates, using two independent experiments.

	Lopez-Villalobos et al (2001)						MacDonald et al (2008)				
	milk yield		Bodyweight		BCS		stockingrate (cows/ha)				
	H	L	H	L	H	L	2.2	2.7	3.1	3.7	4.3
	(kg/cow/d)		(Kg/cow)		(scale 1-10)		pasture DMI (kg/ha/d)				
actual	19.1	17.5	517	453	4.20	4.2	35.5	38.8	45.1	46.0	48.7
predicted	18.8	16.5	504	447	4.21	4.2	32.5	39.0	42.5	48.4	53.3
RPE	0.16	0.20	0.03	0.02	0.06	0.09	0.13	0.09	0.12	0.13	0.16
CCC	0.94	0.87	0.72	0.81	0.18	-0.47	0.77	0.87	0.93	0.91	0.88

Abbreviations: **BCS** = body condition score, **H** = heavy line, **L** = light line, **RPE** = relative prediction error, **CCC** = concordance correlation coefficient

Similarly, CCC values were relatively high and within an acceptable range between 0.87 and 0.94.

The predicted BWs over the eight month of lactation showed an increasing trend in both lines of cows similar to that of the actual values. However the predicted curves did show a small loss of weight in the 2nd and 3rd month post calving that were not observed in the study. The average BW and the predicted final BWs were close to the actual values for both lines of cows, meaning that the model could represent in a reliable way two lines of cows with contrasting sizes. The predicted BW over the lactation showed less proportional discrepancies with actual values than did milk yield with a very good RPE (2 to 3%), but lower CCC values between 0.72 and 0.81.

The predicted values for BCS presented a general trend similar to BW, showing a light decrease by the 3rd month post calving and a later recovery. The predicted curve for BCS was different to the curve for observed values, which showed a small but continuous decrease in **BCS** over the lactation period. The ranges of actual and predicted values for BCS were small and lead to contradictions between measures of model fitness. The CCC values were very poor (-0.47 to 0.18) but the RPE was high (6 to 9%).

Table 1 shows the fitness of the model to predict DMI within a large range of stocking rates. The predicted values were in line with the actual values and the measures of fitness of the model for each stocking rate were within the acceptable ranges.

Figure 4 shows the relationship between actual and predicted values of daily DMI considering the five stocking rates together. Predicted values showed a small deviation from the unity line, confirming the power of the model to predict pasture intake within a wide range of stocking rates without significant bias.

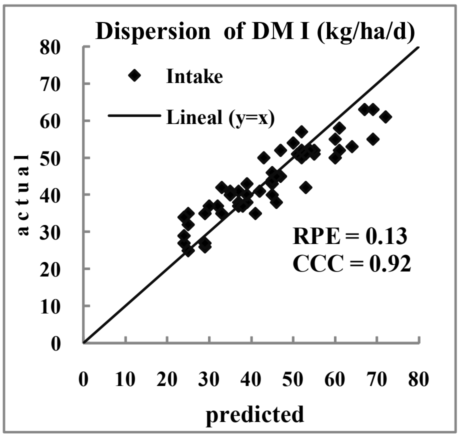

Figure 4. Average monthly pasture intake showing actual vs predicted with unity line for the 5 stocking rates.

The observed milk yield, averaged over the three years and for the 5 stocking rates was 4115 kg/lactation and the predicted value was 4726, implying an over prediction of 14.9 %.

These results indicate that the model can predict with acceptable accuracy average daily pasture intake, milk yield, BW and BCS for cows of contrasting genotypes.

4. CONCLUSIONS

The mechanistic whole dairy farm model developed in this study using a rational approach and basic empirical information at the paddock and individual cow level, has proved to be robust enough to realistically simulate pasture intake and the partitioning of energy between milk and body reserves (BW and BCS) of contrasting genotypes of cows. Although there are some areas to improve predictions (milk yield in early lactation and BCS changes) the annual average output of the model simulated reasonably well to actual data suggesting that it could be used with the initial aim of studying farming strategies over a wide range of pastures and supplements in combination with different cow genotypes.

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