Effects of feeding level and genetic merit on the efficiency of pasture-based dairy systems: field and modelling studies

A thesis presented in partial fulfilment of the requirements for the degree of:

Doctor of Philosophy in Animal Science

At Massey University, Palmerston North, New Zealand

MASSEY UNIVERSITY

Javier Baudracco

2011

Dedicated to Ana

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ABSTRACT

The objective of this thesis was to develop and validate a dynamic and stochastic whole-farm model that can predict physical and economic performance of pasture-based dairy systems; explore interactions between cow genetic merit, feeding level (supplementation and stocking rate) and market prices; and be applied to both ryegrass-based and lucerne-based pasture dairy systems.

The effects of, and interactions between, stocking rate (SR), supplementation and genetic merit of cows on grazing dairy systems were reviewed, approaching both the physical and economic impact of these factors. The performance of strains of Holstein-Friesian cows in experiments from Ireland, Australia and New Zealand was summarised, and a meta-analysis that explores the relationship between herbage allowance and herbage intake was included.

The development of the whole-farm model was completed in three steps. Firstly, a model was developed and validated that predicts herbage intake at grazing for dairy cows with or without supplementary feeding and that combines physical, metabolic and ingestive constraints. Secondly, an animal model that predicts energy intake, milk yield and live weight change of a single cow at grazing (e-Cow model) was developed and validated. This model also integrates the above intake model, a mammary gland model and a body lipid change model. The e-Cow model, which is available as a web-based version, combines nutritional and genetic drives to control energy partitioning within the cow. It also accounts for genetic differences between cows and is sensitive to genotype by environment interactions. The third and final step was the development and validation of a stochastic and dynamic whole-farm model that predicts physical and economic performance of grazing dairy systems (e-Dairy model). Both the e-Cow and the e-Dairy models simulate the performance of individual cows on a daily basis and were developed using Visual Basic programming language.

The validation of the whole-farm model (e-Dairy) was conducted for ryegrass-based dairy systems using existing data from a 3-year farmlet experiment comparing five levels of SR (2.2 to 4.3 cows/ha) conducted in New Zealand, with cows offered 0.15 t dry matter (DM) supplement/cow/year. The validation of the model for lucerne-based dairy systems was performed with data from a 2-year farmlet experiment designed and completed as part of the current research. This experiment compared three

levels of SR (1.6 to 2.6 cows/ha) for cows offered 1.8 t DM supplements/cow/year in Argentina. An indigestible intake marker developed from a purified enriched lignin (LIPE®) was used to estimate individual herbage intake for a short-period within the farmlet experiment.

Stochastic simulations (n=200) using the whole-farm model (e-Dairy) suggest that for ryegrass-based New Zealand dairy systems (ratio $/kg milk to $/kg supplement of 1.1 ± 0.31), the increase in SR from 2.8 to 3.5 cows/ha together with an increase in imported supplements from 0.15 to 1.45 t DM/cow/year can be profitable only when milk price is higher than $NZ5.5/ kg MS ($US4.1). Simulations for lucerne-based dairy systems in Argentina (ratio $/kg milk to $/kg supplement of 1.8 ± 0.55), suggest that the increase in SR from 1.6 to 2.6 cows/ha, with a fixed amount of imported supplements per cow at 1.8 t DM/cow/year would increase operating profit across the range of milk prices tested ($US 3.3 ± 0.84/kg MS).

The e-Dairy model can be used to explore the effects and interactions of feeding level and genetic merit of cows for grazing dairy systems with differing calving patterns as well as evaluating the trade-offs between profit and the associated risk. It could also potentially be used, after further development, to simulate the genetic evaluation of cows and bulls under different selection objectives and selection schemes such as progeny tests for bulls.

ACKNOWLEDGEMENTS

My thanks first to God.

A special thanks to my supervisors Assoc. Professor Nicolas Lopez-Villalobos, Professor Colin Holmes and Dr. Eduardo Comeron. Thanks Nicolas for teaching me so openly and about so many things, for your wise advice and for your unconditional and never-ending support. Thanks Colin for always being there when I needed you and for your tremendous help in designing, carrying out and writing this thesis. Thanks Eduardo for providing everything needed to carry out the experiments and for your great help in improving the thesis.

I gratefully acknowledge the continual support of Professor Kevin Stafford. Many thanks to Massey University, INTA Rafaela, Facultad de Ciencias Agrarias, IVABS and WTARS Trust for their funding that made possible the projects reported in this thesis.

I extend my thanks to Kevin Macdonald for his huge input and also for providing detailed datasets, crucial in validating the models developed in this research. Many thanks to Professor Tom Barry for sharing his wealth of experience and dedicating his valuable time to this research.

The help of Luis Romero, Martin Maciel, Daniel Scandolo and Miguel Taverna with the experiments is very appreciated. Thanks Marcelo Zamateo for sharing with me your wide programming knowledge. Thanks to Luis Rista, Norberto Gariglio, Debbie Hill and Wendy Graham for your constant support. A big thanks to the brave students that helped in the experiments, muchas gracias Cristian Blangetti, Sergio Lenardon, Fernando Zappa, Emilio Marconetti, Adrian Varrone and Pablo Gabrielloni

Many thanks to Belen Lazzarini, Nicolas Friggens and Chris Grainger for the valuable comments and advice. Thanks to my brother Gonzalo Tuñon for sharing his wisdom with me.

A profound thanks to my New Zealand family: Carlos and Gisela Cuadrado, Ronnie and Celina, Belen and Javi, Hernan and Vero, Gonza and Bere, Francisco and Valentina, Naty and Grant, Jose and Elizabeth, Dani and Juan, Aluna, members of the Latin American Soccer Team, and their families.

Massive thanks to my family in Argentina. Gracias viejos, hermanas, suegros, cuñados, tíos y sobrinos; gracias por su incondicional afecto, gracias por alentar mis esfuerzos.

Ana, I thank you for accepting the challenges with me and for being so supportive always, everywhere and with everything, thanks Franci and Santi for the miracle of your shining lives.

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LIST OF ABBREVIATIONS

A	Actual values in validation tests
ADF	Acid detergent fibre
APP	Annual pasture production
BCS	Body condition score
C	Constant rumen capacity
C.DMI	Concentrate dry matter intake
C.IVDMD	In vitro dry matter digestibility of the concentrate
CBW	Calf birth weight in kg
CCC	Concordance correlation coefficient
CP	Crude protein
CSR	Comparative stocking rate (kg live weight/t of total DM offered)
CV	Coefficient of variation
DIM	Days in milk
dL/dt	Rate of change of body lipid
DM	Dry matter
DMI	Dry matter intake
ECM	Energy corrected milk
EG	Efficiency of grazing
EVg	Metabolisable energy value per kilogram of live weight gain
F	Fill effect of diet
FCE	Feed conversion efficiency
FOH	Faecal output from herbage
GH	Growth hormone
H	Matrix of the generated herd
H.IVDMD	In vitro dry matter digestibility of herbage
HA	Herbage allowance
HD	High durability North American Holstein-Friesian cow
HDMI	Herbage dry matter intake
HDMIa	Herbage dry matter intake per cow calculated with the animal performance method
HDMIc	Herbage dry matter intake based on sward cutting method
HDMIi	Herbage dry matter intake based on intake marker method
HE	Harvesting efficiency
HerbDMIo	Herbage dry matter intake of cows fed only pasture
HerbDMIs	Herbage dry matter intake of cows fed supplements
HF	Holstein-Friesian
HM	Herbage mass
HMmax	Herbage mass at which net accumulation rate approaches zero
HP	High productivity North American Holstein-Friesian cow
IGF-I	Insulin-like growth factor
IVDMD	In vitro dry matter digestibility
L	Amount of body lipid mass (kg)
Lignin(sa)	Sulphuric acid lignin
LIPE	Indigestible intake marker (purified enriched lignin)
Lnext	Amount of lipid at the next calving (kg)
LW	Live weight
LWo	Live weight associated with body lipid reserves

LWgr	Live weight gain per day due to growth of young animals
LWp	Live weight gain due to growth of the gravid uterus
MaxLipLoss	Maximal rate of lipid loss
ME	Metabolisable energy
ME from/to BCS change	Metabolisable energy mobilised or synthesised from/to body lipid reserves
ME Potential Milk Yield	Metabolisable energy required for milk synthesis
MEgr	Metabolisable energy for growth in the case of young animals
MEl	Metabolisable energy required to synthesize one litre of milk
MEm	Metabolisable energy required for maintenance
MEp	Metabolisable energy required to maintain pregnancy
MEReq	Total metabolisable energy (ME) requirements
MJ	Mega Joule
MS = MFP	Fat plus crude protein
MSPE	Mean square prediction error
NA	North American
NZ	New Zealand
P	Predicted values in validation tests
PastME	Metabolisable energy concentration of pasture
PercMilkFat	Percentage of milk fat
PercMilkProt	Percentage of milk protein
PGR	Pasture growth rate
PotDMI	Potential herbage dry matter intake for cows fed only pasture
PotDMIe	Metabolic limitation to energy demand
PotDMIg	Grazing limit for herbage dry matter intake
PotDMIr	Physical limitation to rumen fill
R	Pearson coefficient of regression
RPE	Relative prediction error
S.DMI	Silage dry matter intake
S.IVDMD	In vitro dry matter digestibility of the silage.
SD	Standard deviation
SEM	Standard error of the mean
SOL	Coefficient accounting for the effect of stage of lactation on rumen capacity
SR	Stocking rate
SubR	Substitution rate
SuppDMI	Kg dry matter intake of supplement
Target LW	Post-calving live weight at the present lactation
Target LWnext	Post-calving live weight at the next lactation
TFO	Total faecal output estimated with LIPE®
TMR	Total mixed ration
WFM	Whole-farm model

Chapter 1

General introduction

BACKGROUND

Globally, there has been renewed interest in pasture-based dairy systems. This is due to continuing removal of subsidies and tariffs, increments in production costs and land price (Dillon *et al.*, 2005) and perceived environmental and animal welfare concerns associated with intensive dairying (Dillon, 2006).

Genetic merit, stocking rate (SR) and supplementation are three of the main drivers of grazing dairy systems efficiency; however, their effects and interactions are complex. The selection of modern dairy cows, which are highly demanding in terms of nutrients, compromises the simultaneous achievement of high grazing efficiency, high milk yield per cow and target body condition scores (BCS) in grazing dairy systems (Kolver, 2003). Thus, supplements, which are more expensive than pasture, need to be introduced to balance the dual objectives of adequate level of feeding per cow and high herbage utilisation per hectare. However, the inclusion of supplements has strong impact on the profitability of the system.

Field research has been conducted in several countries to explore the effects of these three key components of dairy systems, using ryegrass-based pastures (Fulkerson *et al.*, 2008; Macdonald *et al.*, 2008b; McCarthy *et al.*, 2007; Roche *et al.*, 2006). However, this type of research is very expensive and therefore limited. Modelling studies can complement field research and allow the effect of several key factors to be extrapolated beyond the limits of the experimental conditions.

System modelling involves representation of the key features of a relevant system in mathematical models, which are then used to make inferences about the system (Woodward *et al.*, 2008). Thus, the modelling of dairy systems is a useful tool in the context of changing market prices of milk and feeds, changing policies and changing genetic merit of cows. Basically, a whole-farm model for grazing dairy systems must deal with the prediction of herbage intake at grazing, the prediction of energy partitioning within the cow, *i.e.*, milk yield and live weight (LW) change, and the representation of the whole-farm in terms of physical and economic variables.

Nevertheless, whole-farm models for grazing dairy systems are not abundant, and most of the existing whole-farm models are restricted to use in a particular country or region, since equations to predict intake were developed for the specific conditions. In addition, few whole-farm models account for genetic differences between cows, with very few adapted to grazing dairy cows (Bryant *et al.*, 2005). Those models which account for genetic merit of cows in grazing systems use site-specific breeding values, thus limiting the use of the model to the country where those breeding values were calculated.

Furthermore, the option to simulate either seasonal or all year-round calving systems is not always available in whole-farm models. Finally, whole-farm models that account for stochasticity usually work at a herd level and/or a monthly basis (Shalloo *et al.*, 2004), while whole-farm models for grazing systems simulating individual cows on a daily basis do not account for stochasticity (Hulme *et al.*, 1986; Larcombe, 1990; Beukes *et al.*, 2008; Bryant *et al.*, 2010; Freer *et al.*, 1997).

THESIS OBJECTIVE AND APPROACH

The general objective of this thesis was to develop and validate a dynamic and stochastic whole-farm model to predict physical and economic performance of pasture-based dairy systems, able to explore interactions between genetic merit, supplementation, SR and market prices for systems using either ryegrass-based or lucerne-based pastures.

This thesis aimed to develop a highly versatile whole-farm model for grazing dairy systems. To make the model versatile in terms of type of pasture, different equations were developed to allow the prediction of herbage dry matter (DM) intake from ryegrass-based pastures when allowance is expressed either at ground level or at 4 cm above ground level, and for lucerne-based pasture when allowance is expressed at 4 cm above ground level. To make the model versatile in terms of type of cow, the genetic merit of the cow was defined by potential yields of milk, fat and protein, LW and parameters related to genetic targets for BCS at different stages of the reproductive cycle. In order to evaluate the risk associated with management strategies, key dairy system variables *i.e.*, genetic merit, market prices and pasture production, were allowed to behave stochastically.

The whole-farm model was developed to simulate the performance of individual cows accounting for both nutritional and genetic drives for the prediction of energy intake and its partitioning. The whole-farm model was validated for ryegrass-based dairy systems with a dataset obtained from a farmlet trial comparing five levels of stocking (Macdonald *et al.,* 2008a). Since there is a lack of research on lucerne-based dairy systems, a farmlet experiment comparing three levels of stocking rate was conducted as part of this thesis project to allow the validation of the whole-farm model for lucerne-based dairy systems.

Parameters and equations used to build the model were obtained from Friggens *et al*. (2004), Vetharaniam *et al*. (2003), Baudracco *et al*. (2010a), Kolver *et al*. (2002), Roche *et al*. (2006), Horan *et al*. (2005) and McCarthy *et al*. (2007). Independent datasets were used to validate the whole-farm model.

The whole-farm model developed in the current thesis is a valuable tool to adjust dairy systems to potential future environmental regulations tending to control either greenhouse gas emissions or nutrients leaching. Those regulations could set limits to SR and levels of imported supplement.

THESIS OUTLINE

Chapter 2 reviews the effects of, and interactions between, SR, supplementation and genetic merit of cows on ryegrass-based grazing dairy systems, approaching both physical and economic impact of these factors, and includes a meta-analysis that explores the relationship between herbage allowance and herbage intake.

Chapter 3 reports on a 2-year farmlet experiment conducted to quantify the effects of SR on lucerne-based dairy systems. This Chapter provides a unique discussion comparing dairy farmlet experiments using ryegrass-based and lucerne-based pastures. To our knowledge, this is the first farmlet experiment for dairy cows grazing lucerne-based pastures. Chapter 4 reports on a short-term experiment designed to quantify the effects of herbage allowance on herbage intake of individual cows grazing lucerne-based pastures using an indigestible intake marker developed from a purified enriched lignin (LIPE®).

The remaining Chapters deal with the development and validation of a model that predicts herbage intake at grazing for dairy cows with or without supplementary feeding, combining physical, metabolic and ingestive constraints (Chapter 5), the development and validation of an animal model that predicts energy intake and energy partitioning of a single cow at grazing (Chapter 6, e-Cow model), and the development and validation of a stochastic and dynamic whole-farm model that predicts physical and economic performance of grazing dairy systems (Chapter 7, e-Dairy model). In Chapter 6 and 7, the main characteristics of models similar to e-Cow and e-Dairy are review.

Both the animal model (e-Cow) and the whole-farm model (e-Dairy) were designed to predict whole-lactation performance on a daily basis, accounting for homeostatic and homeorhetic control of body lipid change for cows of different genetic merit and both models are sensitive to genotype by environment interactions. This interaction occurs when animals differ in their ability to perform in different environments (Falconer, 1981).

Chapter 8 contains a general discussion of the thesis and illustrates a practical application of the whole-farm model with two examples of stochastic simulations conducted for both ryegrass-based dairy system in New Zealand and lucerne-based dairy systems in Argentina. Two levels of SR were compared for each system. For ryegrass-based systems, the two farms simulated were a 'low input' farm, similar to the average New Zealand dairy farm (Livestock Improvement, 2010), with 2.8 cows/ha and 0.15 t DM/cow/year of imported supplement, and a 'high input' farm with 3.5 cows/ha and with 1.45 t DM/cow/year of imported supplement. For lucerne-based systems, the performance of the low SR (1.6 cows/ha) and the high SR (2.6 cows/ha) farmlets of the experiment reported in Chapter 3 were simulated, using 1.8 t DM cow/year of imported supplement for both systems. In both sets of simulations, pasture dry matter produced on-farm, milk payout and supplement price were set to behave stochastically.

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Chapter 2

Effects of stocking rate, supplementation, genotype and their interactions on grazing dairy systems: a review

J. Baudracco[1], N. Lopez-Villalobos[1], C.W. Holmes[1] and K.A. Macdonald[2]

[1]Institute of Veterinary, Animal and Biomedical Sciences, Massey University, Private Bag 11-222, Palmerston North, New Zealand

[2]DairyNZ, Private Bag 3221, Hamilton, New Zealand

Published 2010 in New Zealand Journal of Agricultural Research 53: 109-133

ABSTRACT

The main effects of, and the interactions between, stocking rate (SR), supplementation and genotype on dry matter (DM) intake, herbage utilisation, milk production, and profitability of grazing dairy systems have been reviewed.

Stocking rate determines the average herbage allowance per cow and, therefore, has a major effect on herbage intake and on the productivity of grazing dairy systems. In this review, the effect of herbage allowance on herbage intake is presented separately for two groups of studies: those which measured allowance at ground level and those that measured allowance at a cutting height of 3 to 5 cm above ground level.

Herbage intake and milk yield per hectare usually increase as SR increases. However, there is generally an associated reduction in herbage intake and milk yield per cow because of the decrease in average herbage allowance at a higher SR. The dual objectives of adequate level of feeding per cow, and high herbage utilisation per hectare can be achieved with the inclusion of supplements.

The milk response to supplements depends mainly on the size of the relative energy deficit between potential energy demand and actual energy supply. The relative energy deficit determines both energy partitioning within the cow and substitution rate. The relative energy deficit is increased by either a high demand for energy within the cow or by a deficit of dietary energy available to meet the demand. Cows with different genotype differ in their potential for milk yield. Cows with high genetic potential for milk yield undergo higher relative energy deficits under grazing dairy systems, resulting in lower substitution rates, higher milk responses to supplements, but also lower body condition score, which, in turn, lead to lower reproductive performance.

Whole-farm experiments in many countries have demonstrated that the inclusion of supplements, with a concomitant increase in SR, can have synergistic effects in improving the productivity of grazing dairy systems. Overall, the level of supplementation required per cow and the optimum SR depend on the genetic potential of the cow, the size of the responses to supplement, the value of milk and the costs of feeding supplements.

INTRODUCTION

There has been renewed interest internationally in grazing production systems (Macdonald *et al.*, 2008a), as a result of i) reductions in milk prices in many countries; ii) increments in production costs (Dillon *et al.*, 2005) and iii) perceived environmental and animal welfare concerns associated with intensive dairying (Dillon, 2006). This interest has triggered further studies on stocking rate (SR), a topic extensively studied in countries with pasture-based dairy systems since the 1960s. The recent studies have focused on the interactions between SR, supplementation, cow genotype and the efficiency of conversion of feed into milk.

Stocking rate can be defined as the number of cows per unit of land and per unit of time (i.e., annual SR: cows/ha/year; daily SR: cows/ha/day). Daily herbage allowance (kg herbage dry matter offered/cow/day) is a function of herbage mass (kg dry matter/ha), area offered and SR. Herbage allowance (HA) has been identified as a major factor influencing dry matter (DM) intake and animal performance (Combellas & Hodgson, 1979; Holmes, 1987; Meijs & Hoekstra, 1984).

At a low daily SR (high HA), cows are fed generously and produce more milksolids (fat plus protein) per cow than at a high daily SR. However, more pasture is wasted (not eaten) and, therefore, milksolids (MS) yield per hectare is lower. In contrast, at a higher SR (lower HA), less pasture is eaten per cow, MS yield per cow is lower, cows are predisposed to lose more live weight (LW) in early lactation, and lactations are shorter; however, more pasture is eaten per hectare and MS yield per hectare tends to be higher (Bryant *et al.*, 2003a).

In reporting results from many studies investigating the effect of HA on animal performance investigators have discussed their results and have combined the results from experiments measuring HA at ground level with the results from studies reporting HA at a cutting height of about 4 cm (in the range of 3 to 5 cm) above ground level. In the present review, the effects of HA on animal performance are reported separately for those studies that measured HA at ground level and those that measured HA >3 cm above ground level. This distinction has obvious important quantitative implications for the relationship between herbage allowance and herbage intake.

Pasture management must optimise pasture utilisation, production and quality, while cow management must optimise feeding and milk production (Holmes & Roche, 2007). Both these objectives can be achieved by the inclusion of supplementary feeds.

However, milk response to supplements depends on many factors. The genetic potential of the cow and the level of feeding before supplementation (related to HA) are among the most important factors. High yielding cows partition a high proportion of energy towards milk yield (Dillon *et al.*, 2006), but they are not able to meet their requirements without high quality supplements. Nevertheless, when supplements are included, the profitability of pasture-based dairy systems still depends on the efficiency of grazing (defined as herbage intake expressed as a proportion of herbage allowance) and this depends on SR (Macdonald, 1999).

Numerous experiments have investigated different aspects of the effects of SR, supplementation and genotype on the system; therefore, integrating results from those experiments with a whole-farm approach would be very valuable. The objective of this study is to review the effects and interactions of SR (and indirectly HA), supplementation and genetic potential for milk yield on dairy system's performance.

HERBAGE INTAKE AT GRAZING

Intake of herbage has been identified as the main factor limiting milk yield of grazing cows (Leaver, 1985; Dillon, 2006). Herbage intake (HI) is affected by environmental factors such as rainfall and temperature, pasture characteristics such as herbage mass and structure, sward species, herbage quality (Combellas & Hodgson, 1979; Dillon, 2006), and cow characteristics including genetic potential for milk yield (Horan *et al.*, 2006), stage of lactation (Stockdale *et al.*, 1987), LW and parity (Peyraud *et al.*, 1996). Additionally, numerous management factors affect HI, with HA and the quantity and quality of supplements being the most important (Combellas & Hodgson, 1979; Poppi *et al.*, 1987; Dalley *et al.*, 1999).

Herbage allowance is defined as the amount of herbage above a specified sampling height allocated to livestock (kg DM/cow/day). At low HA, non-nutritional factors related to pasture structure determine HI (Poppi *et al.*, 1987). In contrast, at high levels of HA, the relationship between HA and HI becomes asymptotic, with HI increasing at a progressively lower rate as HA is increased (Combellas & Hodgson, 1979; Holmes 1987; Peyraud *et al.*, 1996). At high HA, nutritional factors such as herbage quality and the metabolic demand of the animal appear to be controlling intake through two basic mechanisms: rumen fill and metabolic regulation of intake (Mertens 1987; Poppi *et al.*, 1987).

Physical and physiological factors regulating feed intake change in importance with increasing herbage quality. Neutral detergent fibre (NDF) is an important nutritional factor through its effects on digestion and rumen fill, with a lower rate of digestion and higher rumen fill as NDF in the diet is increased. At high HA, with herbage containing high concentrations of NDF, intake is limited by the physical capacity of the animal, and it becomes a function primarily of dietary characteristics, while with herbage containing low concentrations of NDF, intake is controlled by the physiological energy demands of the animal, and is principally a function of animal characteristics (Mertens, 1987).

Both physiological energy demand and DM intake at grazing are affected by the genotype of the cow. There is evidence of differences between breeds in DM intake and milk production at grazing. The reputed higher intake per unit of LW of Jersey compared with HF have been confirmed in a study comparing production efficiency of HF, Jersey and crossbred HF-Jersey cows at grazing (Prendiville *et al.*, 2009). In this study, Jersey and crossbred HF-Jersey cows had higher DM intake/kg LW and lower milk yield than HF cows. This has major implications on the efficiency of pastoral dairy systems.

Herbage allowance and herbage intake

The relationship between HA and HI depends on the levels of HA being compared (with higher increments in HI per unit of HA at lower HA), the cutting height of the herbage and the level of production of the experimental animals (Stakelum *et al.*, 2007). The height of herbage sampling cut, above which HA is expressed, is an essential factor influencing the relationship between HA and HI (Table 1 and 2, Figure 1).

Herbage allowance is commonly measured at ground level in some countries, such as New Zealand and Australia, but it is usually measured at 4 to 5 cm above ground level in some other countries, including Ireland and United Kingdom. However, perennial ryegrass dominant pastures can have herbage masses of 2.2 to 3.7 t DM/ha below 4 to 5 cm above ground level (Delagarde *et al*., 1997; Ribeiro *et al*., 2005; Kennedy *et al*., 2007a; O'Donovan & Delaby, 2008). Despite the obviously important quantitative difference between techniques, numerous published studies have discussed results of the effect of HA on HI without a clear discrimination between experiments expressing HA measured either from ground level or from a specified cutting height above ground level. Many studies support or contrast their results with previous similar studies, but do not take these differences into account. Therefore, contradictory results were found when describing functions relating HA to HI, increments in HI per kg of HA and the HA at which maximum intake is achieved.

Bargo *et al*. (2003) reviewed seven studies with grazing cows fed only pasture. An equation derived from those experiments predicts that maximum HI is reached at a HA of 110 kg DM/cow/day. In six out of seven of these studies herbage mass was cut at ground level, and in one study was cut at 5 cm above ground level. Delagarde & O'Donovan (2005), compared seven published relationships between HI and HA (measured at ground level), and reported an average of 0.20, 0.15 and 0.11 kg DM per kg DM increase in HI in the ranges of 20 to 30, 30 to 40 and 40 to 50 kg DM HA, respectively. These results are slightly lower than those summarised in this review (Table 2) and also similar to results from Delagarde *et al*. (2001) depicted in Figure 1, all for HA measured at ground level.

In the present review, the relationship between HA and HI has been quantified by performing a meta-analysis based on the results of 31 studies carried out in grazing conditions with perennial ryegrass dominant pastures (Table 1). Data were analysed using the mixed procedure in the SAS package (SAS Version 9.1, SAS Institute Inc., Cary, NC, USA, 2001). As suggested by St-Pierre (2001), study was fitted as a random effect. The height of herbage sampling was included as a class (at ground level or >3 cm above ground level). Only unsupplemented treatments were analysed.

The term meta-analysis may be used in studies that involve a thorough description of the literature search methods, as well as investigation of sources of heterogeneity in the data and assessment of the likelihood of publication bias. In our study, meta-analysis only refers to the process of formulating a quantitative model that best explains the observations from multiple published studies (St-Pierre, 2001).

Table 1 Effect of herbage allowance on herbage intake and herbage utilisation, and effect of supplementation on milk response. Results from 31 grazing experiments with ryegrass-dominant pastures (range of values reported in each experiment).

Reference	Days in milk	Sample height (cm)	Herbage allowance (kg DM/cow)	Herbage intake (kg DM/cow)	Supplement intake (kg DM/cow)	Milk yield (litres/cow)	Energy corrected milk	Harvesting efficiency	Milk response (litres/kg)	Substitution rate (kg/kg)	LW (kg/cow)
Dalley *et al*., 1999	56	0	20-70	11.2-18.5	0.5	25.9-29.1	25.2-28.9	0.26-0.56			516
Dalley *et al*., 2001	29-39	0	40-65	13.6-17.9	0	23.9-26.4	22.6-25.8	0.28-0.34			528
Grainger & Mathews, 1989	51	0	7.6-33.2	6.1-16.0	0-3.2	15.4-23.1	23.5	0.41-0.83	0.15-0.57	0.05-0.75	454
Lee *et al*., 2008	64	0	34.7-37.8	14.7-15.0	0	20.8-23.4	21.2-23.1	0.39-0.43			452
Peyraud *et al*., 1996	147	0	21.0-51.2	14.6-19.3	0	20.1-24.0	19.9-22.8	0.38-0.75			550
Ribeiro *et al*., 2005	150	0	20.5-36.1	14.0-16.7	0.3	18.8-22.6	18.5-20.7	0.45-0.69			593
Robaina *et al*., 1998	180-210	0	17.7-42.3	9.2-14.3	0-4.4	10.6-18.4	10.8-19.0	0.31-0.64			481-538
Stockdale, 2000a	40-63	0	26.7-53.5	13.4-19.3	2.0-2.4	26.7-31.2	24.7-29.1	0.26-0.53		0.4-0.8	513-550
Wales *et al*., 1999	54	0	20-70	6.7-22.3	0	NA	NA	0.34-0.55			525
Wales *et al*., 2001	89	0	18.3-37	10.0-15.6	0	20.7-26.2	18.6-24.1	0.42-0.59	0.19-0.44		520
Wales *et al*., 1998	215	0	15-40	8.0-14.6	0	9.0-15.5	9.3-15.9	0.37-0.53			540
Johansen & Hoglind, 2007	78-96	3	11.2-23.6	10.3-12.7	3.0-3.8	21.4-24.4	20.8-23.1	0.55-0.92			482-506
Maher *et al*., 2003	130	3.5	16.3-24.6	15.1-16.9	0	20.8-23.0	20.1-22.3	0.69-0.93			570-576
Stakelum *et al*., 2007	101-249	3.5	17.0-23.5	15.5-18.2	0	17.1-25.9	18.3-26.0	0.75-0.91			546-562
Burke *et al*., 2008	170	4	14.6-19.6	13.1-17.1	0-4.0	20.7-24.7	19.8-23.8	0.87-1.04	0.79-1.00	0.44-0.54	562-575
Ferris *et al*., 2008	180-206	4	17.9-19.5	13.1-13.3	3.3-3.6	25.1-25.5	24.9-25.6	0.67-0.74			595-609
Kennedy *et al*., 2003	110-200	4	20.0-24.9	13.0-17.6	0-5.4	19.7-31.2	20.3-32.5	0.65-0.72	0.72-1.10	0.41-0.62	NA
Kennedy *et al*., 2007a	98	4	17.2-30.8	13.0-18.6	0	17.4-26.0	16.8-25.0	0.57-0.84			487-525
Kennedy *et al*., 2008	40-80	4	12.8-20.0	11.3-16.5	0-4	21.4-30.9	20.7-28.9	0.71-1.08	0.80-1.78	0.13-0.63	489-531
Kennedy *et al*., 2005	36	4	16	15.1	2.76	28.3	27.7	0.94			599
Kennedy *et al*., 2007b	46	4	13.3-19.0	12.3-15.4	0-4	23.0-28.6	22.2-27.7	0.74-1.06	0.98-1.33	0.25-0.45	489-515
Kennedy *et al*., 2009	210	4	15.4-15.5	12.1-13.8	3	20.9-22.4	21.1-22.2	0.78-0.89			531-540
McEvoy *et al*., 2008	56	4	13.9-18.0	12.5-15.7	0-6.0	25.7-31.6	24.2-30.2	0.75-0.98	0.57-0.80		541
McEvoy *et al*., 2009	168	4	16.8-20.6	15.6-17.6	0	18.0-19.3	18.2-19.3	0.76-1.05			512
Meijs & Hoekstra, 1984	101	4	17.8-28.7	11.9-16.6	0.9-6.3	NA	NA	0.51-0.69			575

Table 1 (Continued) Effect of herbage allowance on herbage intake and herbage utilisation, and effect of supplementation on milk response. Results from 31 grazing experiments with ryegrass-dominant pastures (range of values reported in each experiment).

Reference	Days in milk	Sample height (cm)	Herbage allowance (kg DM/cow)	Herbage intake (kg DM/cow)	Supplement intake (kg DM/cow)	Milk yield (litres/cow)	Energy corrected milk	Harvesting efficiency	Milk response (litres/kg)	Substitution rate (kg/kg)	LW (kg/cow)
Morrison & Patterson 2007	119	4	20.5	8.9-12.9	0-6.3	17.1-21.9	16.8-21.1	0.43-0.63			NA
Sayers *et al*., 2003	75-140	4	23	9.3-13.3	5-10	28.8-40.9	28.6-37.7	0.40-0.58			NA
Delaby *et al*., 2001	217	5	12.1-19.6	11.3-15.0	2.7	24.1-25.9	23.2-24.5	0.71-0.93			597-612
Delaby *et al*., 2003	172	5	17.7-26.2	15.7-18.6	2.5-2.6	20.7-21.5	20.4-21.3	0.71-0.89			671-677
Delagarde *et al*., 1997	186	5	21.9-23.5	14.0-16.8	0.3-2.2	22.7-27.1	20.0-24.3	0.59-0.77	1.39	0.24	635
O'Donovan & Delaby, 2008	195	5	12.7-21.9	13.9-17.0	0	20.3-23.9	19.1-22.0	0.78-1.09			582-589

Sample height= cutting sample height of herbage allowance; Herbage allowance= kg DM/cow/day; Herbage intake= kg DM/cow/day; Supplement intake= kg DM supplement/cow/day; Milk yield= kg milk yield/cow/day; Energy corrected milk= kg milk × (383 × fat % + 242 × protein % + 783.2)/3140 (Tyrrell & Reid, 1965); Harvesting efficiency = kg herbage DM consumed/kg DM herbage allowance; Milk response = Litres energy corrected milk per kg supplement eaten; Substitution rate= Reduction in kg DM herbage intake per kg DM supplement consumed; NA= Not available.

Table 2 Relationship between herbage allowance (HA) and herbage intake (HI) for unsupplemented treatments of studies reported in Table 1.

	Sampling height	
	At ground level	>3 cm above ground level
Number of studies analysed	11	20
HI f(HA) =	$HI = 5.3216 + 0.3447\ HA - 0.00220\ HA^2$	$HI = 6.6999 + 0.6824\ HA - 0.01105\ HA^2$
HA at Maximum intake (kg DM/cow/day)	78.4	30.9
Maximum HI (kg DM/cow/day)	18.8	17.3
Average increase (kg DM intake/kg DM HA)		
From 10 to 20	0.28	0.35
From 20 to 30	0.24	0.13
From 30 to 40	0.19	
From 40 to 50	0.15	
From 50 to 60	0.10	

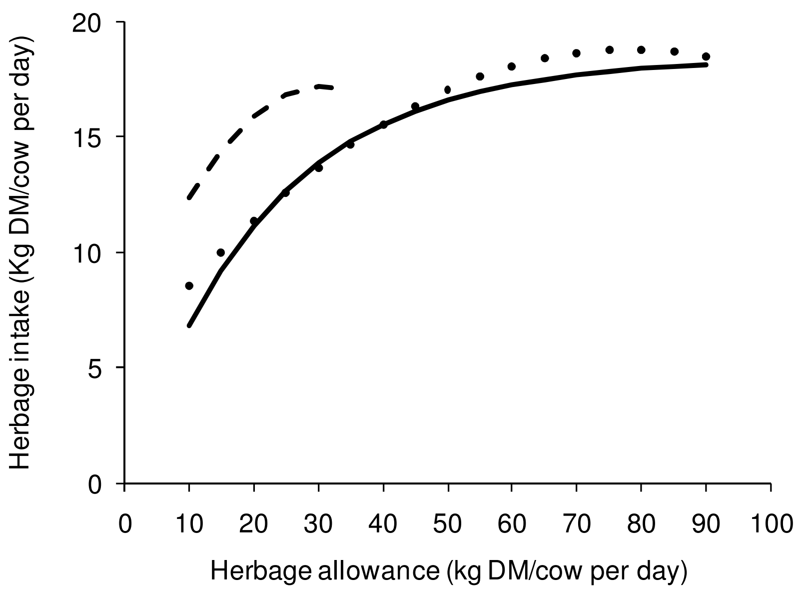

Figure 1 Relationship between herbage allowance (HA) and herbage intake (HI) of dairy cows. Data from unsupplemented treatments of the experiments of Table 1 reporting herbage allowance: at ground level (●); >3 cm above ground level (- - -) and at ground level according to the equation reported by Delagarde *et al.* (2001) (▬).

Based on Akaike's Information criteria, the models that fitted the data best were: HI = 5.3216 + 0.3447 HA - 0.00220 HA^2 (CV = 13.4%; R^2 = 0.80; n = 49), for studies reporting sampling height at ground level and HI = 6.6999+ 0.6824 HA - 0.01105 HA^2 (CV = 7.7%; R^2 = 0.61; n = 50), for studies reporting sampling height >3 cm above ground level. From these Equations, HA for maximum HI were 78.4 and 30.9 kg DM when HA is expressed at ground level and >3cm above ground level, respectively. Further details of the relationship between HA and HI found for experiments of Table 1 are given in Table 2.

SUBSTITUTION RATE

When supplements are consumed by grazing cows, DM intake of pasture is usually reduced (Kellaway & Porta, 1993; Holmes & Roche, 2007). This effect is called substitution, because supplement is substituting for pasture. The substitution rate (reduction in kg DM HI per kg DM supplement consumed) increases as HA increases (Meijs & Hoekstra, 1984; Grainger & Mathews, 1989; Penno *et al*., 2006).

With the inclusion of highly digestible concentrates, an increase in total digestibility of the whole diet can be expected. However, the rapidly fermentable energy provided by concentrates may also cause a reduction in ruminal pH, reduces the rate of fibre digestion, and consequently causes a reduction of HI (Dixon & Stockdale, 1999; Walker *et al*., 2001). These have been called negative associative effects between the supplement and the pasture (Dixon & Stockdale, 1999).

Another cause of substitution is a reduction in grazing time (Bargo *et al*., 2003). This could be considered an indirect cause, because the main cause is the reduction in the relative energy deficit of the cow (less hunger), as feed allowance is increased by feeding supplements while maintaining HA. The relative energy deficit is the amount of energy consumed by a cow relative to her demand, and increases due to a high demand for energy by the cow, and/or a deficit of dietary energy to meet demand (Grainger, 1990; Penno *et al*., 2001; Holmes & Roche, 2007). Previously, and in agreement with this concept, Meijs & Hoekstra (1984) concluded that the effects of the factors influencing substitution rate may partly be related to the difference between the intake of nutrients from herbage and the nutrient requirement. Therefore, animal, sward, supplements and management factors that increase the relative energy deficit of the cow will decrease substitution rate.

Animal factors

When supplements were fed to cows with high energy demands (high proportion of NA genes) lower substitution rates were found in several recent studies (Kennedy *et al*., 2003; Horan *et al*., 2005a; Kolver *et al*., 2005; Fulkerson *et al*., 2008;) in comparison to cows of lower energy demand (lower proportion of NA genes) (see Table 3). Parity and stage of lactation may also influence substitution rate and milk response to supplements through their influence on potential DM intake and the relative feed deficit. The effect of these factors is discussed later (see section on milk response to supplementation).

Sward factors

Sward factors such as pasture species and pasture quality may also influence substitution rate. Grass-dominant pastures showed greater substitution rate (0.16 kg DM/kg DM) than white clover-dominant pastures (Stockdale, 2000b). If physical or chemical characteristics of the pasture limit the feed intake of the grazing cow relative to her feed requirements, total feed intake is likely to be highly responsive to additional supplements, with a low substitution rate (Penno *et al*., 2006). This is discussed further in the section below titled pasture availability and quality.

Management factors

Management factors such as HA and the quantity of supplement determine the energy intake of the cow, which affect the relative energy deficit of the cow and substitution rate (Holmes & Roche, 2007). Two similar equations have been proposed to predict the substitution rate (kg decline in HI/kg supplement):

Substitution rate = 0.315 HDMI – 0.445 (CV = 34.7; r.s.d = 0.13); (Grainger & Mathews, 1989).

Substitution rate = 0.21 HDMI – 0.18 (CV = 42.8; r.s.d = 0.16); (Stockdale, 2000b).

where HDMI is herbage DM intake expressed as kg DM/100 kg LW.

In long-term experiments using farmlet systems, annual substitution rates with high SR were 0.53 at high (1.7 t DM/cow) and 0.22 at medium (0.84 t DM/cow) levels of concentrate feeding in Australia (Fulkerson, 2000), and 0.28 with about 1 t DM fed per cow as maize silage, maize grain or a mixed ration in New Zealand (Penno, 2002). In these experiments, substitution was managed for the benefit of the farm through intentionally sparing pasture that could be used at a later time with minimal loss in quality. Further discussion related to substitution rate is found below in the milk response to supplementation section.

STOCKING RATE

The importance of SR on dairy farm efficiency has been recognised for many years. Initially, SR was expressed simply as cows per hectare and used as a simple measure of the ratio between feed demand and feed supply (McMeekan, 1961). The number of cows gives a measure of the annual feed demand, while a hectare provides a measure of the amount of feed (pasture) available. Obvious differences between breeds and genetic strains in LW, and the increased use of supplementary feeds, has resulted in this definition becoming increasingly uninformative and misleading (Holmes & Roche, 2007). An improved expression, comparative stocking rate, was reported by Penno (1999).

Comparative stocking rate

Herd LW provides a better measure of the potential feed demand than the number of cows per hectare and, likewise, the total amount of feed provided gives a more accurate quantification of feed supply than the area farmed. This suggests that a ratio of total herd LW to total feed supply is a more useful measure of the SR relationship. This is called comparative SR (CSR)(Penno, 1999) and is expressed as:

$$CSR = \frac{kilogrames\ LW\ per\ hectare}{tonnes\ total\ DM\ offered\ per\ hectare}$$

where total DM includes pasture grown and all other feeds.

This expression takes account of differences in LW between and within breeds, and of the extra feeds imported, although it does not account for either the effects of differences in genetic merit for milk yield (Holmes & Roche, 2007; Macdonald *et al*., 2008a) or quality of feeds.

EFFECTS OF STOCKING RATE ON THE DAIRY SYSTEM

Stocking rate is recognised as one of the most powerful management tools available for dairy farmers in pastoral systems (McMeekan, 1961). For a particular amount of pasture produced annually per hectare, SR determines the annual HA per cow, and indirectly the average daily HA (Holmes, 1987). This strongly affects the productivity and profitability of the system.

Herbage utilisation and milk production

The efficiency of grazing has been defined in two ways: herbage consumed at each defoliation, expressed as a proportion of the herbage mass originally present; or the herbage consumed expressed as a proportion of herbage accumulation, generally in one year (Hodgson, 1979). The first is also referred to as harvesting efficiency and the second as herbage (or pasture) utilisation in the present review.

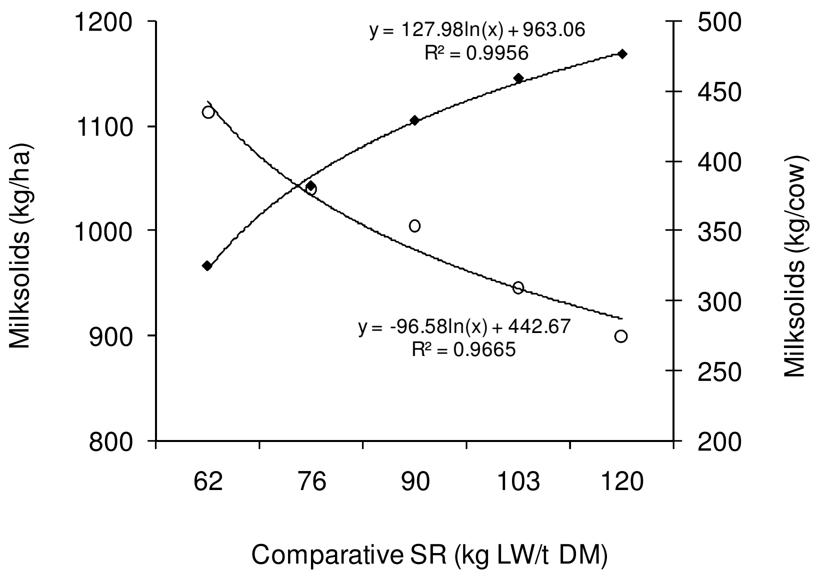

Figure 2 The effects of comparative stocking rate on milksolids (fat and protein) production per cow (○) and per hectare (●). Theoretical values from the original paper were used for comparative stocking rates. Comparative stocking rates were calculated as expected LW/ha (kg LW/cow × SR) divided by expected total DM produced per hectare/year. Redrawn from Macdonald *et al.* (2001).

The effects of SR on pasture production, pasture utilisation, energy partitioning within the cow and system productivity can be illustrated with data from a New Zealand study over three years, which investigated the effects of SR on dairy farm efficiency

(Macdonald *et al.*, 2001, 2008a). Five treatments were created by stocking five farmlet systems with different numbers of New Zealand Holstein-Friesian (HF) cows per hectare (2.2, 2.7, 3.1, 3.7 and 4.3 cows/ha) on pasture-only systems (only 136 and 190 kg DM/cow/year as imported supplements in the systems with 3.7 and 4.3 cows/ha, respectively). Details and results of this experiment are shown in Table 4 and Figure 2 and 3.

At higher SR, herbage accumulation and herbage utilisation (herbage eaten/herbage accumulation) were increased, resulting in an increase of MS production per hectare. However, pasture intakes per cow and MS yield per cow were reduced at higher SR (Table 4 and Figure 2).

Figure 3 shows that as comparative SR increased, a decreasing proportion of the energy produced from pasture was wasted in the form of pasture not eaten, an increasing proportion was converted into milk and an increasing proportion was used for cow maintenance. In summary, Figure 3 shows that at the lowest comparative SR the system was inefficient because of the low pasture utilisation due to pasture wastage. At the highest comparative SR, the system reduced its efficiency because of low feed conversion efficiency, due to the higher proportion of energy consumed from pasture being used for cow maintenance.

The relationship between comparative SR and annual pasture utilisation is shown in Figure 4. The regression equation derived from these data indicates that as comparative SR increases from 60 to 100 kg LW/t DM, annual pasture utilisation increases from 66% to 85%, with an average increment rate of 4.6% for every 10 kg LW/t DM of increment in comparative SR. In contrast, systems which fed concentrates in farmlet studies in US (Fales *et al.*, 1995) and Australia (Valentine *et al.*, 2009) showed low or nil changes in pasture intake and pasture utilisation as SR increased, because SR and supplementation per hectare were both increased simultaneously in these studies. However, even though comparative SR was not reported in these two studies, it can be inferred that comparative SR was similar across treatments within each study.

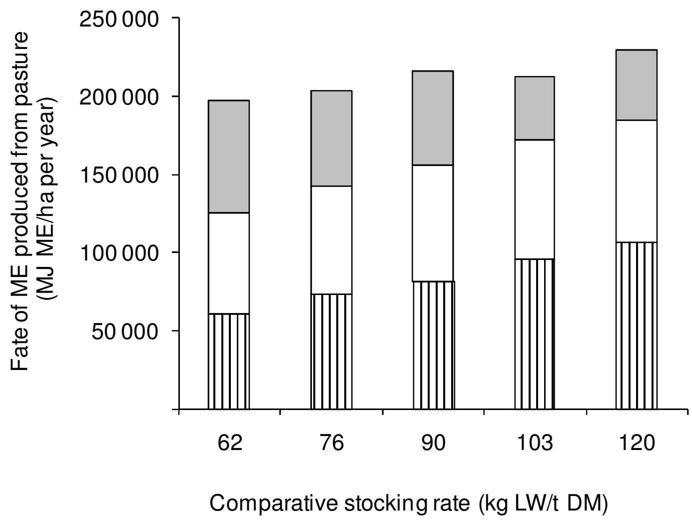

Figure 3 Fate of the metabolisable energy (ME) supplied from net herbage accumulation in a pasture-only system as comparative stocking rate increased. Data from Macdonald *et al.* (2001), assuming that 67 mega joules of ME were retained per kg milksolid (MS) synthesised. The entire bar represents ME produced from pasture per hectare per year; (■) ME not consumed; (□) ME consumed and converted into milk and (‖) ME used for cows' maintenance.

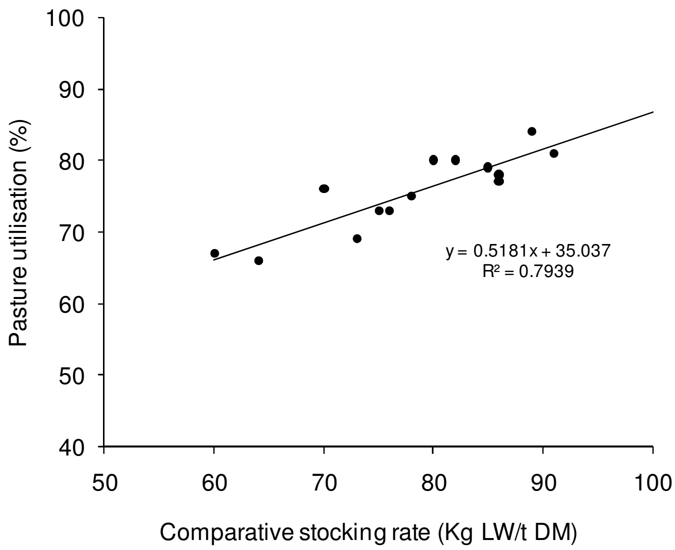

Figure 4 Relationship between comparative stocking rate (kg LW/t DM total offered) and pasture utilisation from data in Table 4 (Macdonald *et al.*, 2001; Jensen *et al.*, 2005; Hedley *et al.*, 2006). Supplementation ranged from 0 to 20 t DM/ha/year among treatments in these studies. Actual comparative SR values were used for Macdonald *et al.* (2001).

Pasture production

In perennial plant species (such as perennial ryegrass), the growth of new tissue and the loss of mature tissue to senescence and decomposition occur simultaneously (Hodgson & White, 2000). At very high SR (low HA) defoliation can be so intense, or so frequent, with subsequent low herbage mass (Stockdale & King, 1980; Korte *et al*., 1987) that interception of solar radiation and herbage accumulation are reduced. Alternatively, lax or infrequent defoliation, associated with low SR, may create pastures with very high herbage mass, thus resulting in high senescence losses and reducing the rate of net herbage accumulation in tall swards (Korte *et al*., 1987; Hoogendoorn *et al*., 1992). The key tools of grazing management are frequency and intensity of grazing, and its timing relative to the condition in the pasture (Holmes & Roche, 2007).

Annual pasture production (net herbage accumulation) increased from 17.5 to 19.8 t DM/ha as SR increased from 2.2 to 4.3 cows/ha for the experiment reported by Macdonald *et al*. (2001, 2008a), which is summarised in Table 4. This supports the concept of increased pasture accumulation as grazing pressure increased from low grazing pressure. In this experiment, the grazing pressure at the higher SR was not so extreme as to cause detrimental effects on pasture accumulation, and may have allowed pastures to remain close to their optimum herbage mass. In contrast, in an experiment exploring the effect of SR (2.5, 2.9, 3.3, 3.6 and 4.1cows/ha) on the dairy system, Valentine *et al*. (2009) reported no effect of SR on pasture production. However, in the latter experiment, cows were fed supplements and pasture consumed represented less than 34% of the diet in all SR treatments in dryland farmlets. The availability of supplements in this experiment allowed similar pasture management (pre and post-grazing herbage mass) in all farmlets, which is probably the reason why SR had no effect on pasture production.

Pasture quality

Post-grazing residual masses determine the quality of pasture in subsequent grazing with lower post-grazing residuals giving higher pasture quality at the next grazing. Ensuring that post-grazing residuals are low (*i.e*. 1.5 t DM/ha) should, therefore, be a priority, but must be balanced against the reduced HI caused by grazing to lower residuals (Holmes & Roche, 2007). On an annual basis, SR can influence post-grazing residuals and, therefore, the nutritive value of pastures (Holmes & McMillan, 1982).

Metabolisable energy (ME) per kg DM increased from 11 to 11.4 mega joules (MJ) of ME as SR increased from 2.2 to 4.3 cows/ha in the experiment of Macdonald *et al*. (2001), a consequence of lower herbage mass and lower senescence losses in the systems with higher SR. Hoogendoorn *et al*. (1992) reported that low mass swards (2.5 t DM/ha) contained higher proportions of grass leaf and lower proportions of grass stem and dead material and were more digestible than high mass swards (5.3 t DM/ha). Optimum post-grazing residual masses will vary across countries because of different sward characteristics. Suggestions of optimum post-grazing residual masses can be found in Holmes & Roche (2007) and in Dillon (2006) for conditions in New Zealand and Ireland, respectively.

System profitability and interactions among SR, supplementation and genotype

Interactions between SR, supplementation and cow genotype can be understood through their effects on feed demand and feed supply, and their consequent effects on the productivity and profitability of the farm. Both SR and cow genotype affect feed demand. Furthermore, cow genotype not only affects the quantity of feed demanded but also the quality of feed required. Supplements affect the quantity and quality of feed offered in the system, which in turn affect the efficiency of pasture utilisation and the efficiency of conversion of feed into milk.

The optimum SR is that which gives the maximum sustainable profitability per hectare. Although MS production per hectare increases as SR increases, total farm costs also increase at higher SR, because each extra cow requires expenditure on labour, health and production (Holmes *et al*., 2002).

Stocking rates for maximum economic performance of New Zealand HF and Jersey cows were predicted for New Zealand conditions by Penno (1999), based on previous New Zealand trials (Ahlborn & Bryant, 1992; McGrath *et al*., 1998). For a dairy farm producing 16 t DM/ha/year, the SR that maximised farm profit per hectare were 3.6 and 2.7 cows/ha for Jersey and HF cows, (equivalent to comparative SR of 84 and 85 kg LW /t DM) respectively.

The SR which gives the maximum profit may cause some reduction in milk yield per cow. Thus, using the equation from data plotted in Figure 2, for HF cows, it was calculated that, as comparative SR progressed from 60 (low SR) to 85 kg LW/ t DM (close to the SR with maximum economic profit), MS production per cow was reduced by 20%, from 425 to 342 kg MS/cow.

Milk and supplements prices affect the SR for maximum economic profit. From Table 4 it can be observed that the comparative SR for maximum economic profit were 84 (Jensen *et al.*, 2005), 92 (Macdonald, 1999), 81(Macdonald *et al.*, 2001) and 80 (Hedley *et al.*, 2006). These differences may be due to differences in the ratio milk/supplements price ($/kg milk ÷ $/kg supplement purchased) and in the amount of supplements used. The Jensen *et al.* (2005) and Hedley *et al.* (2006) studies reported that maximum economic profit was achieved with 10.0 and 11.6 t of DM/ha imported supplement, respectively. In these two studies, the milk/supplement price ratio was 2.0 and 1.7, respectively. By contrast, in the experiments of Macdonald (1999) this ratio was close to 1, and maximum economic profit was achieved when no supplements were imported (Table 4). Macdonald *et al.* (2001) used almost no supplements. In addition, the fixed costs associated with every cow will affect the SR for maximum profit.

The economic performance of grazing dairy systems is also affected by cow's breed. Production data from Australian dairy farms were analysed with an economic model to compare the operating profit of two farm systems with either HF or crossbred HF-Jersey cows (Pyman *et al.*, 2005). These authors reported higher profit for systems with crossbred cows, and the difference was explained by higher SR of crossbred herds (because of their lower LW) and superior reproductive performance resulting in longer survival and reduced investment in replacement costs.

Table 3 Effects of the proportion of North American (NA) Holstein Friesian (HF) genetics on milk yield, milk response to supplement, substitution rate and pregnancy rate (cows pregnant/100 cows) for pastoral dairy systems. Results from whole lactation experiments.

Reference	Duration (years)	Strain – treatment	NA genetics (%)	Supplement (T DM/cow per year)	Total milk yield (litre/cow)	Milk response[1] (litres/kg.)	Substitution rate[2] (kg/kg)	Pregnancy rate[3] (%)
Horan *et al*., 2005a	3	HP-MP	90	0.3	6799			
		HD-MP	80	0.3	6408			
		NZ-MP	13	0.3	6039			
		HP-HS	90	0.3	6283			
		HD-HS	80	0.3	6176			
		NZ-HS	13	0.3	5940			
		HP-HC	90	1.3	7877	1.3	0.19	79[4]
		HD-HC	80	1.3	7360	1.1	0.41	85[4]
		NZ-HC	13	1.3	6444	0.5	0.51	91[4]
Kennedy *et al*., 2003	3	MM-LC	Not A.	0.4	Not A.	-	-	Not A.
		MM-MC	Not A.	0.8	Not A.	1.1[5]		Not A.
		MM-HC	Not A.	1.5	Not A.	1.0[5]		Not A.
		HM-LC	Not A.	0.4	Not A.	-		Not A.
		HM-MC	Not A.	0.8	Not A.	0.7[5]		Not A.
		HM-HC	Not A.	1.5	Not A.	1.1[5]		Not A.
Kolver *et al*., 2005	2	NA	>87	0	6112	-	-	53
		NA	>87	0.8	7114	1.0	0.67	67
		NA	>87	1.6	7827	0.9	0.67	53
		NZ	<13	0	5568	-	-	84
		NZ	<13	0.8	6365	0.7	0.63	78
		NZ	<13	1.6	6632	0.4	0.75	95
Macdonald *et al*., 2008b	3	NZ70	<7	0	4,811		Not A.	94
		NZ90	<24	0.4	5593	0.6	Not A.	91
		NA90	>91	0.8	5479	1.0	Not A.	82
(Fulkerson, 2000)	5	LGM	17	0.3	4508	-	-	83
(Fulkerson *et al*., 2008)		LGM	18	0.8	5241	0.9	0.65	90
		LGM	20	1.7	5776	0.7	0.54	84
		HGM	59	0.3	4951	-	-	70
		HGM	61	0.8	5779	1.0	0.22	79
		HGM	63	1.7	6451	0.9	0.53	81

[1]Litres of milk per kg supplement eaten. [2]Reduction in kg DM herbage intake per kg DM supplement consumed. [3]Percentage of cows in calf at end of mating period.[4]Average of three feeding systems. [5]Early lactation.

HP= High productivity; HD= High durability; MP= Feeding system with low concentrate: 350 kg concentrate/cow/year; HS= High stocking; HC= High concentrate system; MM= Medium genetic merit; HM= High genetic merit; LC= Low concentrate; MC= Medium concentrate; NZ= New Zealand; NZ70= 1970s New Zealand low genetic merit HF; NZ90= New Zealand high genetic merit HF; NA90= NA high genetic merit HF; LGM= Low genetic merit; HGM= High genetic merit; Not A. =Not available.

Recent studies have shown genotype by environment interactions (Dillon *et al*., 2006), indicating that the most appropriate strain of HF cow will differ depending on the feeding system used. Stocking rate and supplementation can be considered as factors that change the environment for the cow, since they change the level of feeding of the cow.

These findings have implications on pastoral dairy systems, given that, for example, from 1980 to 1999 the average amount of North American (NA) genetics in HF dairy cows of New Zealand increased from 2 to 38% (Macdonald *et al*., 2008b) and the use of NA HF genetics has increased in Ireland from 9% in 1990 to 65% in 2001 (Horan *et al*., 2006). From Table 5, it can be observed that experiments in both Ireland and New Zealand reported the maximum economic profit for HF cows with a low percentage of NA genetics, for experimental conditions based on grazed pastures and low to moderate concentrate supplementation level (between 0.3 and 1.5 t DM/cow/year).

Results from the New Zealand HF strain trial (Table 3 and table 5) carried out by Macdonald *et al*. (2008b) and also reported by Kolver *et al*. (2004), compared three strains of HF genetics: New Zealand cows from the 1990s (NZ90), New Zealand cows from the 1970s (NZ70) and 1990s NA HF (NA90) (Kolver *et al*., 2004), under pastoral-seasonal calving systems. Annual feed allowances ranged from 4.5 t DM/cow (only pasture) to 7.0 t DM/cow (pasture, maize silage and maize grain). Under the conditions of this trial, NZ90 cows produced more MS than NA90 cows and generated higher profit across all the pasture-based systems evaluated.

Economic profit per hectare was maximised at a comparative SR of 92 kg LW/t DM (5.5 t DM/cow) for NZ70 cows, 85 kg LW/t DM (6 t DM/cow) for NZ90 and at 85 kg LW/t DM (6.5 t DM/cow) for NA90. These SRs would be equivalent to 3.1, 2.8 and 2.6 cows/ha if they could be managed on pastures growing 17 t DM/ha. This shows that the NA90 cows required more feed, and in this case more supplementary feed (maize silage and maize grain), in order to maximise profits, compared with NZ90 cows. Therefore, the optimum SR and comparative stocking rate will vary according to the genetic potential for milk yield of the cow.

Genetic selection has produced changes in HF cows, other than milk production, which also affect the profitability of the system. Higher proportions of quarters were affected by mastitis in NA HF cows than in NZ HF (Lacy-Hulbert *et al*., 2002; Macdonald *et al*., 2008b). Furthermore, cows with higher economic breeding index, either NA HF or NZ HF, had equal or improved locomotion ability, less severe hoof disorders and less clinical lameness than cows of lower economic breeding index. These differences between genetic groups were generally constant at either low or high concentrate feed systems (Olmos *et al*., 2009).

Reproductive performance

Higher SR may cause longer periods of anoestrus and reduced fertility due to potentially lower feed intakes and lower body condition score (BCS) at calving (McGowan, 1981; McDougall *et al*., 1995). These adverse effects can be overcome by feeding sufficient supplements (Macdonald, 1999).

The effects of SR on postpartum anoestrus were studied on grazing dairy cows by McDougall *et al*. (1995). Two levels of SR were used with either New Zealand HF (3.0 and 4.0 cows/ha) or Jersey (3.5 and 4.5 cows/ha) cows. In both breeds, the high SR herds finished the trial with a lower BCS, LW and milk production per cow and had longer periods of postpartum anoestrus. Body condition score and MS production were inversely related to the interval between calving and postpartum ovulation.

The percentage of cows (New Zealand HF) that were anoestrus at the start of mating was higher at a high SR than at a lower SR (Macdonald, 1999), but when supplements were fed at the high SR, anoestrous problems were reduced. In addition, differences in the days to resumption of oestrus activity have been observed for cows of different HF strains. Results from Macdonald *et al*. (2008b) showed that the NA90 cows resumed oestrus activity more quickly after calving than the NZ90, but that this did not result in an earlier or higher in-calf rate.

Table 4 Pasture production and utilisation, milk production and economic result of whole-farm studies (field and modelling) in New Zealand and Australia.

Reference	SR (cows/ha)	Milk price/ Suppl. price	Pasture production (t DM/ha/y)	Pasture utilisation (%)	Supplements imported (t DM/ha/y)	Milksolid yield (kg/cow/y)	Milksolid yield (kg/ha/y)	Comp. SR (kg LW/t DM)	Relative economic profit ($ per ha/ $ per kg MS)	SR at maximum profit/ha	T of suppl. at maximum profit/ha
Hedley *et al*., 2006[1]	3.4		19.0	77		352	1212	86	588		
Modelling	3.6	~1.7	19.0	78	0.8	360	1293	86	621	4.2	
	3.9		19.2	79	2.6	380	1480	85	673	cows/ha	
	4.2		19.4	80	6.2	443	1860	82	775	80 kg LW/t	11.6
	4.5		19.9	80	11.6	522	2350	80	849	DM	
Jensen *et al*., 2005[2]	3.0	~2.0	17.5	73		390	1162	75	618		
Field trial (2 years)	3.0		17.5	69		363	1087	73	545		
	2.6		15.0	66		424	987	64	612	5.2 cows/ha	
	3.8		17.5	79	5	411	1573	85	729	84 kg LW/t	10
	5.2		20.5	75	10	427	2215	78	845	DM	
	6.9		20.5	79	20	416	2867	85	619		
Macdonald, 1999	3.34	~1.0	16.7	NA		311	1040	100	482	3.34	0
Penno *et al*., 1996	3.34		18.2	NA		362	1208	92	539	cows/ha	
	3.34		20.2	NA		395	1317	83	534	92 kg LW/t	
Field trial (3 years)	4.42		18.7	NA	0.3	269	1190	116	441	DM	
	4.42		20.6	NA		299	1325	107	480		
	4.42		18.7	NA	6.0	400	1768	89	188		
	4.42		18.7	NA	5.7	364	1606	91	475		
	4.42		18.7	NA	6.3	407	1800	88	173		
Macdonald *et al*., 2001	2.2	~1.8	17.5	67		435	967	60[3]	591		
Macdonald *et al*., 2008a	2.7		17.9	76		380	1043	70[3]	597	3.2 cows/ha	0
Field trial (2 years)	3.2		18.8	73		353	1105	76[3]	609	81 kg LW/t	
	3.7		18.3	84	0.5	309	1145	89[3]	571	DM	
	4.3		19.8	81	0.8	274	1168	91[3]	517		
Stockdale *et al*., 1998	1.4	NA	NA	NA	0.4	400	560	NA	174		
Ellinbank Dairy Research	2.4	NA	NA	NA	2.4	436	1046	NA	174	1 cows/ha	4.9
Field trial (3 years)	4.1	NA	NA	NA	4.9	392	1517	NA	276		

[1]Hedley *et al*. (2006). Description of 5 systems representing best practices based on what the best farmers of Waikato region are doing. [2] Jensen *et al*. (2005). Values for pasture production are targets, not measured. [3] Actual values of comparative SR, which are lower than values originally expected by the authors. Milk price/Suppl. price= Ratio of price of 1 kg of milk to the price of 1 kg of supplement; Pasture utilisation = pasture eaten/pasture grown; Comp. SR= Comparative SR: kg LW/ t DM offered; Relative economic profit ($ per ha / $ per kg Ms) = Economic profit ($/ha/year) divided MS price ($/kg), price per Kg milk fat used for Stockdale *et al*. (1998); T suppl. at maxim profit= t DM supplements/ha/year for the treatment with maximum profit in the experiment; NA = Not available.

Holstein-Friesian cows with NA genotype (high genetic potential for milk yield) have lower reproductive performance than cows of lower genetic potential, as shown in Table 3 and Figure 5. The experiments summarised in Table 3 were carried out in Ireland (Horan *et al*., 2005a; Kennedy *et al*., 2003), Australia (Fulkerson *et al*., 2008) and New Zealand (Kolver *et al*., 2005; Macdonald *et al*., 2008b) on grazing dairy systems with supplementation ranging from 0.3 to 1.7 t DM/cow/year. In these experiments, even when higher levels of concentrate supplementation were offered (up to 1.5 t concentrate/cow/year) the NA HF strain still had reduced reproductive performance (Macdonald *et al*., 2008b; Horan *et al*., 2005b). Average pregnancy rate declined from 88.8% for treatments with low proportion of NA genetic (<24%) to 79.3% for treatments with high proportion of NA genetic (>59%) in the experiments summarised in Table 3 and depicted in Figure 5.

Lucy *et al*. (2009) demonstrated that the NA90 have a greater BCS loss during early lactation than the NZ90 and this was associated with elevated blood growth hormone (GH) and low blood insulin-like growth factor (IGF-I) concentrations. This then has a flow on effect to lower the reproductive ability of the NA90 cows at all feeding levels compared with the NZ90. Additional feed allowance to the NA90 cows failed to change blood IGF-I concentrations or BCS loss whereas, with the NZ90 additional feed allowance shifted IGF-I concentrations and reduced BCS loss in early lactation.

In addition, better reproductive performance was observed for crossbred HF-Jersey than for HF cows. Percentages of cows confirmed pregnant by week 14 after the first day of inseminating were 86 vs. 78% (Auldist *et al*., 2007) and 84 vs. 77% (Pyman *et al*., 2005) for HF-Jersey and HF, respectively, in studies with cows from commercial dairy farms of Australia.

SUPPLEMENTARY FEEDS IN GRAZING DAIRY SYSTEMS

The inclusion of supplementary feeds in the dairy system affects the HI of cows and, therefore, the productivity and profitability of the system. In this review, the terms *supplementary feeds* and *supplements* refers to both concentrates and conserved forages either imported or produced on-farm.

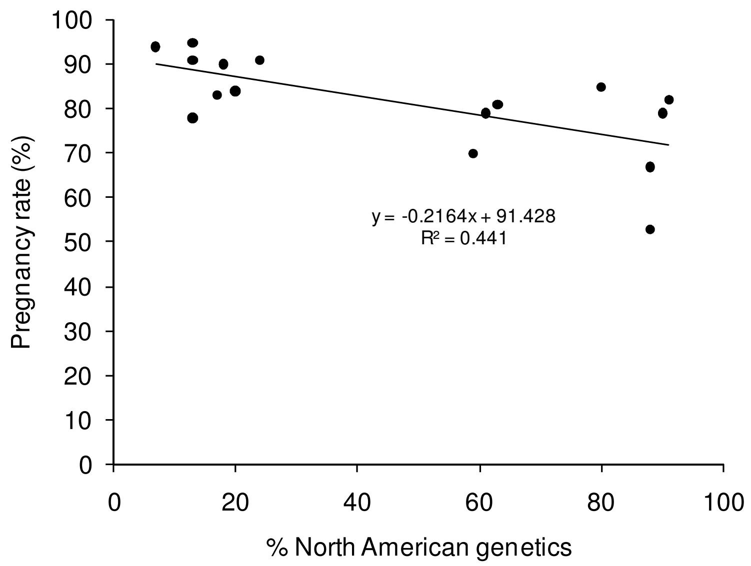

Figure 5 Relationship between the percentage of North American genetics and pregnancy rate for Holstein Friesian cows in Australia, New Zealand and Ireland (Horan *et al.*, 2005a; Kolver *et al.*, 2005; Macdonald *et al.*, 2008b; Fulkerson *et al.*, 2008). All 4 experiments were carried out in grazing dairy systems with a range of imported supplements from 0.3 to 1.7 t DM/cow/year.

Rationale

As discussed above, low SR may lead to high residual herbage mass and wastage of pasture while high SR leads to low production per cow, due to lower HA per cow and to shorter lactations. Thus, SR creates a conflict between a focus on production per cow or per hectare (Stockdale *et al.*, 1998). Furthermore, cows with high potential for milk production cannot express their potential when fed only pasture at grazing. Systems based on grazed pastures can limit daily feed intake by 20% in HF cows, due to a combination of slower rates of intake and digestion (Kolver, 2003). These physical limitations can be reduced by increasing the energy concentration of the diet through concentrate supplementation (Buckley *et al.*, 2005).

Feeding supplements may enable pasture utilisation to be increased in the long term for the whole system, because it gives the manager the confidence to increase grazing pressure, through increases in SR. Higher SR allow efficient grazing of most of the available pasture at peak pasture production, creating seasonal deficits which can then be filled with supplementary feed. This ensures that pasture can be kept in a leafy and rapidly growing phase (Macdonald, 1999), and the dual objectives of maintaining good individual performance (productive and healthy cows) while still allowing pasture to be well utilised (Stockdale *et al*., 1998) can be achieved.

Pasture utilisation and milk yield per cow can be maintained while simultaneously increasing SR and supplementation. For example, herbage utilisation was kept in a relatively narrow range in the experiment of Jensen *et al*. (2005) where supplements were introduced in a range from 0 to 20 t DM/ ha and SR was increased from 3.0 to 6.9 cows/ha (Table 4), and in the experiment of Valentine *et al*. (2009), where SR increased from 2.5 to 4.1 cows/ha and supplements fed increased from 11.2 17.8 t DM/ha from the lower to the higher SR.

The relative energy deficit, between potential energy demand and actual energy supply, is a key driver of the response to supplements. High stocking rates, the use of cows with high genetic potential, such as cows with NA HF genotype, and long lactations are the main drivers of this energy deficit (increasing energy demand), which must then be filled with supplements.

Milk response to supplementation

Milk response to supplementation can be defined as the increase in milk yield per kg of DM supplement offered. A negative relationship exists between substitution rate and milk response to extra feed. Lower substitution rates are associated with higher total DM intake and consequently higher milk response to supplements (Stockdale *et al*., 1998; Bargo *et al*., 2003; McEvoy *et al*., 2008). Responses to supplementary feeds are highly variable. This is because they depend on a wide range of factors, involving the cows, feeds and management systems.

If all the ME from extra feed consumed were converted into milk, 1 kg of MS would be produced, approximately, with an extra intake of 68 MJ of ME by a 500 kg LW New Zealand HF cow (Holmes *et al*., 2002). Therefore, 1 kg DM intake as supplement (12 MJ ME/kg) would allow a theoretical milk response of 176 g MS (2.3 litres of milk 7.7% MS). This is the maximum possible response from extra feed, assuming that all supplementary feed is consumed and all energy converted into milk (Holmes & Roche, 2007). However, in practice, responses will be lower than the maximum possible, because the consumption of supplementary feed usually causes some decrease in pasture consumption (substitution) and some increase in LW gain.

When the immediate and the carry-over effects of including supplements in a pastoral system are added, the total response to extra feed will almost always be smaller than the expected response (Holmes & Mathews, 2001). Average responses from 78-99 g MS/kg DM supplemented (with 12 MJ ME/kg DM) has been reported for whole-lactation experiments (Clark, 1993; Penno, 2002; Macdonald, 1999), which is around 1 kg milk/kg DM supplemented. Kellaway & Porta (1993) reviewed experiments using supplementary feeds in Australia and concluded that when pasture allowance was restricted, offering concentrates was likely to result in an immediate effect of 0.5 kg milk/kg concentrate fed (about 41 g MS/kg DM). However, Bargo *et al.* (2003), in a review of grazing experiments, reported that milk production increased linearly as the amount of concentrate increased from 1.8 to 10 kg DM/cow/day, with an immediate milk response of 1 kg milk/kg concentrate for high yielding dairy cows. In agreement with these previous studies, Dillon (2006) reported that up until the early 1990s, average substitution rates published were around 0.6, resulting in a immediate response of approximately 0.4 to 0.6 kg of milk per kg of concentrate, with most of these studies carried out with low- to moderate-yielding cows (15 to 25 kg/cow/day). Lower substitution rate (0.40) and higher immediate milk response (0.92 kg of milk/kg of concentrate) were found for recent studies (Dillon, 2006).

Average immediate milk responses of 0.88 kg of energy corrected milk (ECM) per kg of supplement and average substitution rate of 0.36 were calculated from experiments summarised in Table 1 (recent experiments). The higher response to concentrate supplementation with higher genetic merit cows may be attributed to greater nutrient partition to milk production than with lower genetic merit cows (Dillon, 2006). Differences in milk response for cows of different genotype are discussed in a later section (genetic potential for milk production). The factors explaining differences between observed and theoretical responses to supplementation are discussed in the following sections.

FACTORS AFFECTING MILK RESPONSE TO SUPPLEMENTATION

The size of the response to extra feed depends mainly on the need for extra feed by the cow. Large responses will be achieved only if the current performance of the cows is being severely limited by the lack of feed (Holmes & Mathews, 2001). After the physical losses of feeding supplements has been discounted, the response to supplements depends largely on the substitution effect of supplements and on factors affecting energy partitioning of extra feed towards either milk synthesis, gain or loss of LW or maintenance.

Relative feed deficit and supplement response

Penno *et al*. (2001) reported that the factor exerting the greatest influence on marginal MS response to supplementary feeds is the cow's relative feed deficit. Because energy is usually the limiting factor in grazing dairy systems (Nicol & Brookes, 2007), the relative feed deficit can be expressed as a "relative energy deficit" which expresses the amount of energy consumed by a cow relative to her demand, and increases due to either a high demand for energy within the cow or a deficit of dietary energy to meet demand (Holmes & Roche, 2007).

Stage of lactation

The stage of lactation can affect the magnitude of milk response to supplements because energy is partitioned more towards BCS and less towards milk synthesis as lactation progresses (Broster & Broster, 1984). It was reported that the immediate milk response to supplements was greater in early lactation, decreasing thereafter (Stockdale *et al*., 1998; Kellaway & Harrington, 2004), but Grainger (1990) and Penno *et al*. (2006) found no effect of stage of lactation on the milk production response.

Recent farm systems trial results suggest that at moderate SR, milk responses to supplementary feeding are low in spring (early lactation for spring-seasonal-calving systems), and improve as the season progresses (Penno *et al*., 1998). In a grazing trial, Clark (1993) reported immediate responses of 26, 16 and 66 g MS/kg DM when 5 kg pasture silage DM/cow/day was offered for 30 days in spring, summer and autumn, respectively.

Similarly, Penno (2002) found no effect of stage of lactation on substitution rate or marginal milk response in grazing cows offered a common diet, suggesting that differences in substitution rate and milk responses are probably caused by differences in pasture quality and not by stage of lactation. Robaina *et al.* (1998) found that milk responses to grain feeding in mid-late lactation cows grazing summer pastures ranged from 0.7 to 1.5 kg of milk/kg of grain consumed, depending on HA and level of grain fed. They suggested that pasture availability and quality seem to dominate responses to concentrate feeding under pasture-based systems.

These results are in agreement with previous explanations suggesting that in experiments with cows at different stages of lactation, some of the differences in marginal response could have been due to differences in diet quality (Grainger, 1990). In grazing systems, the effect of stage of lactation is confounded with the effect of seasonal changes in herbage quality and sward structure (Stakelum *et al.*, 2007). In seasonal pastoral dairying systems, the energy and nutrient requirements of the herd are closely related to stage of lactation, and energy and nutrient supply are closely associated with season of the year (Holmes, 1987). Grazing cows generally undergo restrictions in either pasture availability (in order to harvest pastures efficiently) or quality, which may create higher relative feed deficits in mid or late lactation than in early lactation (Penno *et al.*, 1998). Therefore, the relative feed deficit determines responses to supplements that are independent of stage of lactation in grazing dairy systems (Holmes & Roche, 2007).

Genetic potential for milk production

Genetically improved cows (for milk production) partition a greater proportion of the energy consumed into milk production and less into BCS (Dillon *et al.*, 2006). This enables them to express greater marginal responses to supplementary feeds than low genetic merit cows (Roche *et al.*, 2006b).

The MS response to supplementation of grazing HF cows with different potential for milk production was recently studied in New Zealand (Kolver *et al.*, 2005;

Macdonald *et al*., 2008b) Ireland (Kennedy *et al*., 2003; Horan *et al*., 2005a,b) and Australia (Fulkerson *et al*., 2008). These experiments are summarised in Table 3. In all five experiments, cows with a higher proportion of NA genetics were larger, produced more milk with lower MS concentration, and lost more BCS during lactation.

As depicted in Table 3 and Figure 6, HF cows with a high proportion of NA genetics (>59%) gave greater milk responses to concentrates (average 1.03 kg milk/kg DM supplemented) than cows with a low proportion (<24%) of NA genetics (average 0.63 kg milk/kg DM supplemented). This may be explained by the fact that cows with a higher proportion of NA genetics had a greater relative feed deficit when fed generously on pasture (Linnane *et al*., 2004) and divert more of their energy consumed into milk production than cows with lower proportion of NA genetics. The response to supplementation showed more variation for cows with low proportion of NA genetics than for cows with high proportion of NA genetics (Figure 6). This is due to the inclusion of both NZ90 and NZ70 cows in two of the trials used to plot Figure 6. These strains of HF cows differ in their responses to supplementation, even when they have both low proportion of NA genetics.

The greater relative feed deficit in cows with higher proportion of NA genetics is partly attributable to the low ability of these cows to achieve high levels of HI as a percentage of LW (Kolver *et al*., 2002). The greater proportion of energy partitioned towards milk production of cows with higher proportion of NA genetics is explained by differences in blood hormones between HF strains. Uncoupling of the somatotropic axis in early lactation, whereby the liver fails to produce IGF-I in response to increased circulating GH, is typical of high-producing dairy cows. This is associated with reduced expression of the liver-specific GH receptor (GHR). It was reported a genetic strain effect on IGF-I and GH concentrations, with NA HF having lower IGF-I and greater GH concentrations, indicating a greater degree of uncoupling. This is associated with greater loss of BCS and greater milk production in NA HF than in NZ HF (Kay *et al*., 2009).

The intercalving BCS profile is similar to an inverted milk lactation curve, declining as milk production peaks and replenishing lost body reserves as the milk lactation profile declines. Consistent with this mirror image analogy, cows with superior genetics for milk production (elevated lactation profile) have a depressed BCS profile (Roche *et al*., 2009).

Results of experiments reviewed by Dillon *et al*. (2006) indicate that the extra loss in BCS in NA-high genetic merit cows is not compensated for even when these animals are supplemented with higher levels of concentrate in early lactation, because extra energy is partitioned towards milk synthesis. Additionally, these high yielding cows partition less energy towards BCS in late lactation, resulting in thinner cows at the end of lactation (Roche *et al*., 2006a). As a consequence, NA HF cows require extra supplement after dry-off, to allow them to regain their lost BCS (Holmes & Roche, 2007).

Therefore, genetic selection has altered the response to supplements and the stage of lactation when feed must be offered to achieve increases in BCS. Based on data from Table 3, average substitution rate was higher (0.62 kg DM pasture/kg DM concentrate) for cows with less than 24% NA genetics than for cows with more than 59% NA genetics (0.45 kg DM pasture/kg DM concentrate).

Table 5 Average farm profit for two similar Holstein Friesian (HF) strain trials carried out in Ireland (NZ= New Zealand Holstein-Friesian, HD=high durability North American (NA) HF and HP=high productivity North American HF) and New Zealand (NZ90=New Zealand high genetic merit Holstein-Friesian, NA90= North American high genetic merit HF, and NZ70= 1970s low genetic merit New Zealand Holstein-Friesian).

	Strain	NA genetics (%)	Average farm profit (€ or $NZ/ha/year)	Supplements brought in (t DM/cow/year)
McCarthy *et al*., 2007[1]	HP	>90	€ 551	0.4 to 1.5
	HD	>80	€ 779	
	NZ	<13	€ 899	
Kolver *et al*., 2004[2]	NZ70	<7	$NZ 970	0 to 1.5
	NZ90	<24	$NZ 1509	
	NA90	>91	$NZ 1074	

[1]McCarthy *et al*. (2007): Milk price according to milk quota applied at the industry level: € 0.264, € 0.246 and € 0.246/litre for NZ, HD and HP strains, respectively.
[2]Kolver *et al*. (2004): Averaged over a four farm systems ranging from all-grass to high input. Data are from the second year of the strain trial (2002/2003) at a $NZ 3.60/kg milksolids payout.

A study investigating energy partition of Jersey cows confirmed similar trends, as occurs in HF, Jersey cows of high genetic merit for milksolids partitioned more energy to milk than low genetic merit cows for a range of feeding levels on grazed pasture, which resulted in increased BCS loss and greater negative energy balance for high compared with low genetic merit cows (Bryant *et al.*, 2003b)

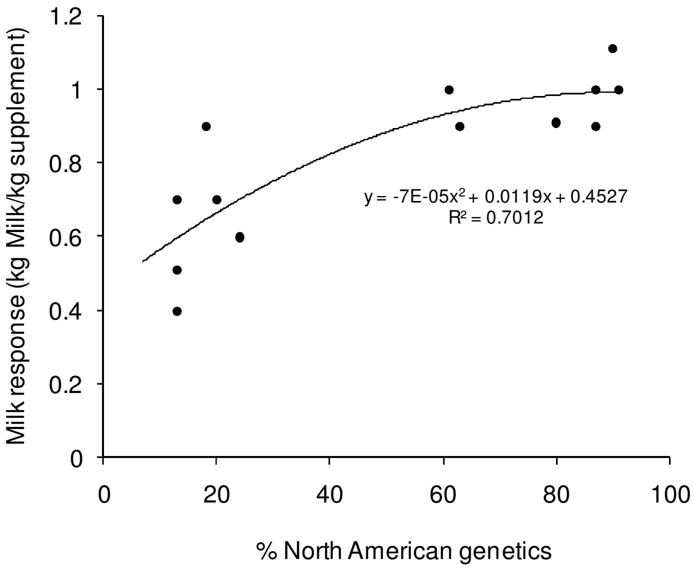

Figure 6 Effects of the proportion of North American genetics on milk response to supplementation (kg milk yield/kg DM supplement eaten). Results from four whole-lactation studies with Holstein cows in Australia, New Zealand and Ireland. Experiments were carried out in grazing dairying systems with a range of imported supplements from 0.3 to 1.7 t DM/cow/year (Horan *et al.*, 2005a; Kolver *et al.*, 2005; Fulkerson *et al.*, 2008; Macdonald *et al.*, 2008b).

Pasture availability and quality

As HA increases, total HI and milk yield usually increases, but the response to supplementary feeds is likely to decrease (Stockdale *et al.*, 1998; Stockdale, 2000b; Penno *et al.*, 2001). This is the result of a higher substitution rate and probably more energy from supplements partitioned towards LW, which will depend on the genetic merit of the cow.

Bargo *et al*. (2003), in a review of the effect of supplementation on pasture DM intake of high yielding NA HF dairy cows at grazing, stratified treatments of the studies reviewed as either low HA (<25 kg DM/cow/day) or high HA (>25 kg DM/cow/day). They found that the substitution rate averaged 0.20 kg pasture/kg concentrate (range: 0 to 0.31) at low HA and 0.62 kg pasture/kg concentrate (range: 0.55 to 0.69) at high HA. Herbage allowance was expressed at ground level in six out of seven of these experiments.

Average prediction of substitution rate using the equations of Stockdale (2000b) and Grainger & Mathews (1989) are 0.29, 0.46 and 0.63 for pasture DM intakes of 12, 15 and 18 kg DM, respectively (assuming a 500 kg LW cow).

There is a positive relationship between herbage quality and substitution rate when concentrates are fed (Holmes & Jones, 1964). As herbage quality deteriorates substitution rate decreases. When ruminants consume high intakes of high digestibility forages (*i.e*. DM digestibility >65 - 70%), the voluntary intake is likely to be limited by metabolic mechanisms. If grain is included in the diet, the animal will largely replace ME from forage with ME from grain. In contrast, when ruminants are consuming low to medium digestibility forages, rumen fill mechanisms are expected to limit intake, and therefore, the magnitude of the substitution should depend on the extent to which dietary grain changes rumen fill (Dixon & Stockdale, 1999).

This is supported by lower substitution rates observed in cows grazing tropical grasses (low quality) compared with cows grazing temperate grasses of higher quality (Combellas *et al*., 1979). Similarly, lower responses to concentrate supplementation were reported in spring compared with summer (Stockdale, 1999) because of the higher energy content of spring grass. If either physical or chemical characteristics of the pasture limit intake, response to supplementation is likely to be high, with a low substitution rate (Macdonald, 1999; Penno *et al*., 2006).

Quantity and quality of supplementary feeds

As total energy intake is increased with the use of supplementary feeds, a declining proportion of the extra energy is partitioned towards milk production and an increasing proportion is partitioned towards body reserves (Penno *et al*., 2001).

Therefore, the marginal MS response decreases as the level of supplementation increases. This can cause a curvilinear response in MS production to concentrate, instead of a linear response (Kellaway & Harrington, 2004).

The reduction in the marginal response to the addition of supplements may be attributed not only to increased partitioning of nutrients to LW gain but also to increased substitution rate as the amount of supplements is increased (Meijs & Hoekstra, 1984). In addition, grain fed to dairy cows at levels greater than 6 kg DM/cow/day may have detrimental effects on digestion in the rumen (Robaina *et al.*, 1998). High intakes of grain may reduce the digestion of forage and increase the amount of starch escaping digestion (Stockdale *et al.*, 1987). This effect can be more important at low levels of forage intake and high levels of concentrate intake, *i.e.*, high ratio of concentrate to forage.

Milk production responses to concentrate reached a plateau at 4 kg DM of concentrate/cow/day when HA was high but with a linear response up to 6 kg DM when HA was restricted (Delaby & Peyraud, 1999). Several reviews and experiments suggest 4 to 5 kg DM/cow/day as the maximum amount of concentrate fed before milk response declined (Kellaway & Porta, 1993; Robaina *et al.*, 1998; Walker *et al.*, 2001). For each additional kg DM of concentrate eaten, substitution increased by 0.03 kg DM/kg DM (Stockdale, 2000b).

Furthermore, the point at which the response in milk per kg of DM supplement starts to decrease and the type of response (linear or curvilinear) depends on the genetic merit of the cow. Milk production increased linearly as the amount of concentrate increased from 1.8 up to 10 kg DM/cow/day in the experiments reviewed by Bargo *et al.* (2003). Those experiments used cows of high genetic merit for milk production and the average response was high, 1 kg milk per kg DM concentrate consumed.

Stockdale (2000b) reported that the substitution rate for feeding forage supplements, such as hay and maize silage, was 0.08 kg DM pasture/kg DM higher than that from feeding concentrates at any given level of unsupplemented HI, based on a review of 39 experiments with grazing dairy cows.

At high HA, supplementation with grass silage resulted in a large reduction in HI, with average substitution rate of 1.17 kg DM pasture/kg DM silage (Phillips, 1988). The higher levels of substitution rate with forages compared with concentrates appear to result from large reductions in grazing time, 15 to 43 min/day for each kg of silage DM consumed (Stockdale, 2000b). This reduction, higher than that reported for concentrates supplementation, is probably due to the potentially slow rate of digestion of forage in the rumen and its relatively poor whole-tract digestibility. The expected higher substitution rate of forages is most likely to be an issue when supplement feeding levels and HA are high (Stockdale, 2000b). At low levels of both HA and supplementation, the fill effect of diet is low and therefore, substitution rate is expected to be low, even when high NDF feeds such as grass silage are used.

CONCLUSIONS

Stocking rate determines the average annual HA per cow and, consequently, SR has important effects on HI, pasture utilisation, milk production per cow and per hectare, and the profitability of grazing dairy systems. From a clear distinction between experiments expressing HA at ground level or above a cutting height, it emerged that HA for maximum HI were 78.4 and 30.9 kg DM when HA is expressed at ground level and >3cm above ground level, respectively.

Partitioning of energy within the cow and substitution rate seem to be the principal underlying mechanisms that explain differences in milk responses to supplementary feeds. The relative feed deficit is a key driver of the response to supplements, since it affects both the partitioning of energy and substitution rate. As the relative feed deficit increases, the response to supplements increases. The relative feed deficit increases due to either a high demand for energy within the cow or a deficit of available dietary energy to meet demand. Therefore, it is affected by the genetic and physiological potential for milk production, and the quantity and quality of pasture and supplements, among other factors.

Genetic selection focused on individual milk yield has produced a cow (NA HF strain) that has an increased short-term milk response to supplements, reduced BCS, reduced fertility and also an inability to meet her requirements without high quality supplements. Consequently, this cow has limited suitability for grazing dairy systems, particularly under high SR and seasonal calving systems.

A synergistic effect can be obtained by increasing the SR and including supplementary feeds. This combination may allow high pasture utilisation, moderate levels of milk production per cow, high levels of milk production per hectare and the highest profitability. However, the level of supplementation required per cow and the optimum SR depend on the genetic potential of the cow, the price of milk and the cost of feeding supplements and managing the extra cows. From the Irish and New Zealand experiments reviewed, the maximum economic profit was obtained with HF cows with a low percentage of NA genetics, under experimental conditions based on grazed pastures and moderate concentrate supplementation (0.3 to 1.5 t DM/cow/year).

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Chapter 3

Effects of stocking rate on pasture production, milk production and reproduction of supplemented crossbred Holstein-Jersey dairy cows grazing lucerne pasture

J. Baudracco[1,3], N. Lopez-Villalobos[1], L.A. Romero[2], D. Scandolo[2] M. Maciel[2], E.A. Comeron[2], C.W. Holmes[1] & T.N. Barry[1]

[1] Massey University, Institute of Veterinary, Animal and Biomedical Sciences, Private Bag 11-222, Palmerston North, 5301, New Zealand.

[2] Instituto Nacional de Tecnología Agropecuaria (INTA), AIPA, Ruta 34 Km 227, (2300) Rafaela, Santa Fe, Argentina.

[3] Facultad de Ciencias Agrarias, Universidad Nacional del Litoral, Kreder 2805, Esperanza, CP: S3080HOF, Argentina.

Published in 2011 in Animal Feed Science and Technology 168: 131-143

ABSTRACT

Effects of stocking rates of 1.6, 2.1 and 2.6 cows/ha on farm efficiency were evaluated using 92 crossbred Holstein-Jersey cows in a completely randomised design for two years in Argentina. A 44.1 hectare farm was divided into three farmlets and one spring calving herd was allocated to each. Cows grazed on lucerne based pastures (*Medicago sativa L.*) and were supplemented with high tannin sorghum silage (S*orghum bicolor*) produced on farm plus imported concentrates (1.8 t dry matter (DM) concentrate/cow/year in all treatments). Stocking rate (SR) had no effect on pasture production, quality, persistence or botanical composition. Efficiency of grazing (herbage consumed/herbage allowance × 1000; g/kg DM) increased with increasing SR (P<0.05), being 143 g/kg DM higher for high SR (2.6 cows/ha) than for low SR (1.6 cows/ha). Herbage DM intake and total DM intake per cow decreased as SR increased (P<0.05), but the decrease was only significant in mid lactation. Yields of milk and fat per cow per lactation did not differ between treatments, however milk protein yield per cow was lower for medium SR cows (P<0.05) and a tendency (P=0.063) for a decline in milk production per cow at higher SRs occurred. Live weight and body condition score were not affected by SR. As SR increased from 1.6 to 2.6 cows/ha, herbage DM consumed increased by 2.4 t DM/ha/year (P<0.05), milk yield increased by 5840 kg/ha/year (P<0.05) and milk solids yield (*i.e.*, fat plus protein) increased by 443 kg/ha/year (P<0.05) with no serious animal health or reproductive issues from year-round grazing of legume pastures. Results show that the theoretical reductions in milk yield per cow expected at higher SR compared to lower SR were prevented by using supplemental feeds, mainly in early lactation.

INTRODUCTION

In grazing dairy systems where pastures are the primary source of feed, stocking rate (SR) is a major factor determining system efficiency (McMeekan & Walshe, 1963; King & Stockdale, 1980; Fales *et al.*, 1995). Recently, there has been a renewed interest in researching SR, a consequence of reductions in milk prices, increases in production costs (Dillon *et al.*, 2005), substantial increases in land prices, and perceived environmental and animal welfare concerns associated with intensive dairying (Dillon, 2006).

A unique characteristic of dairy farms in the main dairying region of Argentina is that feeding is mainly based on year round grazed lucerne pasture (*Medicago sativa L.*) (Collino *et al.*, 2005), in combination with silage, hay and relatively inexpensive concentrates (ratio $/kg milk to $/kg supplement between 1.5 and 2.0; Hemme, 2009).

Dry matter intake per cow and individual animal performance are reduced when the efficiency of grazing (EG; herbage consumed/herbage allowance × 1000; g/kg DM) exceeds 500 g/kg DM (Danelon *et al.*, 2002). However, it is widely accepted that, when EG is low, increasing SR increases efficiency of grazing, as well as productivity and profitability per ha (Stockdale & King, 1980; Fales *et al.*, 1995).

The EG lucerne pasture in Argentina is low, usually less than 650 g/kg DM (Danelon *et al.*, 2002), which is associated with a low SR (average 1.2 cows/ha) and low milk production per ha (average 6086 kg/ha/year; Chimicz & Gambuzzi, 2007). However, the milk price in Argentina is usually among the lowest in the world (Hemme, 2009), which suggest that the profitability of dairy systems can be increased by increasing efficiency of utilisation of the less expensive feed source, grazed pastures, by increasing stocking rate without further increase of supplementation per cow. A comprehensive farm survey (Chimicz & Gambuzzi, 2007) has shown a positive relationship between SR and productivity and profitability of Argentine dairy farms. However, possible adverse effects of higher SR on pasture persistence, milk yield per cow, fertility and health of the cow must be considered.

Internationally, farmlet studies have explored effects of SR on systems which offered pasture only in New Zealand (Macdonald *et al.*, 2008) and Australia (King & Stockdale, 1980) and on systems which offered concentrates in the USA (Fales *et al.*, 1995), Ireland (Dillon *et al*., 1995) and Australia (Valentine *et al*., 2009), but all of these studies used ryegrass based pasture rather than lucerne.

Studies in Australia and New Zealand have frequently used farmlets to explore effects of factors such as stocking rate, genetic merit or supplementary feeding levels on system performance. Farmlets are small herds used to represent a whole farm system (Chataway *et al*., 2010). To our knowledge, this kind of field whole farm research, exploring relationships between SR, EG and milk production per cow and per ha has not been conducted in Argentina. Our objective was to compare production, quality, persistence and utilisation of pastures, milk production and reproduction for crossbred Holstein-Jersey dairy cows stocked at three SR over two years, grazing lucerne pastures and offered a common amount of silage per farmlet and a common amount of concentrate per cow across all farmlets.

MATERIALS AND METHODS

The experiment was designed to quantify changes in pastures and animal performance at three SR within whole farm systems over two years. The experiment was conducted at the experimental research station of the Instituto Nacional de Tecnologia Agropecuaria located in Rafaela, Santa Fe, Argentina, at latitude 31.11S, longitude 61.33W and altitude 99m. The study started on 1 July 2007 and finished on 30 June 2009. This experiment was approved by Massey University Animal Ethics Committee: MUAET protocol 07/67.

The climate is continental, with cold, dry winters and hot summers. Mean annual rainfall is 956 mm (historic data from 1930 to 2006), with 707 mm from October to March inclusive. Mean maximum and minimum temperatures are 31.9 and 17.9^{o}C in January and 15.9 and 5.3^{o}C in July, respectively.

Soils were a complex comprised of Typic Argiudoll (0.35), Acuic Argiudoll (0.55) and Typic Argialboll (0.10). The A horizons (14 to 22 cm depth) had granular or blocky structures with silty clay loam texture (700g/kg silt and 270g/kg clay) and organic C of 14.6g/kg to 15.1g/kg, and the Bt1 horizons (40 to 63 cm depth) had prismatic or columnar structures with silty clay loam or silty clay texture, 600g/kg silt and 380g/kg clay (INTA, 1991).

Farmlet design

Ninety two spring calving crossbred Holstein-Jersey dairy cows were randomly allocated to three farmlets, stocked at either low (1.6 cows/ha), medium (2.1cows/ha) or high (2.6 cows/ha) SR in a completely randomised design. Each farmlet was comprised of four paddocks. Farmlets were balanced on the basis of soil characteristics, average plant density/m^2 (June 2007) and pasture production in the two years previous to the experiment.

Twenty-four cows were allocated to the low SR farmlet (15.0 ha), 31 cows to the medium SR farmlet (14.6 ha) and 37 cows to the high SR farmlet (14.5 ha). Cows did not graze outside their farmlet at any stage of the experiment. Pastures were mixtures of lucerne, white clover (T*rifolium repens*), red clover (T*rifolium pratense*) and prairie grass (*Bromus catharticus*). The grazing areas were 13.0, 12.6 and 12.5 ha for the low, medium and high SR, respectively. Two hectares per farmlet were cropped with sorghum (S*orghum bicolor*) for silage every year, which was sown in October. Stocking rates, calculated only for the grazing areas, were 1.9, 2.5 and 3.0 cows/ha for the low, medium and high SR farmlets, respectively.

Animals

Crossbred Holstein-Jersey cows were selected from the spring calving herd of INTA Rafaela Research Station, with a range from 0.75 Holstein to 0.75 Jersey genes in individual cows. In the first year, there were 80 experimental cows (46 multiparous) and 12 non-experimental cows (animals used to achieve the target SR, but from which no data were collected). After the first lactation, 19 experimental cows were culled on the basis of reproductive failure and health and replaced with non-experimental cows. Thus, 61 experimental cows remained for the second year (all multiparous), and the planned SR was achieved with 31 non-experimental cows. Non-experimental cows were selected in order to maintain homogeneity across the treatments.

At the beginning of the experiment, cows were randomly allocated to ensure that treatment groups were balanced for calving date (August 9 ± 27 d), lactation number (2.2 ± 1.4), proportion of Jersey genes (0.46 ± 0.16), pre-experimental BCS on a scale 1 to 5 (2.8 ± 0.3), pre-experimental live weight (497 ± 66), and average economic genetic merit of $USA13.6. The economic genetic merit is an index which measures net farm income per ton of DM consumed. It was calculated as the sum of breeding values for live weight and lactation yields of milk, fat and crude protein weighted by their corresponding economic values derived from the milk payment and farm costs. Breeding values for each cow were estimated from production data of their previous lactations with a repeatability animal model (Harris *et al*., 1996). This model has been used for the analysis of data when multiple measurements on the same trait are recorded on an individual. In these experimental cows the genetic evaluation considered a Holstein cow as the base reference for comparison.

Mean LW at the first day post-calving were 460 ± 61 kg and 477 ± 58 kg for the first and second year of the experiment, respectively. In the second year, experimental cow characteristics were: calving date (July 30 ± 22 d), lactation number (2.9 ± 1.3) and Jersey genes proportion (0.48 ± 0.17).

Animal management

Uniform management was applied to all cows in all farmlets. Calving occurred from 1 July to 30 September 2007 and from 3 July to 16 September 2008. There was no hormonal induction of calving. Oestrous detection was with the aid of tail paint and daily visual observations of oestrous behaviour (20 min each in AM and PM in each farmlet).

All cows were presented for veterinary examination two days before the planned start of mating to check gynaecological status and cyclicity. A transrectal ultrasonography with a 6-MHz probe (Aquila, Esaote-Pie Medical, Maastricht, The Netherlands) was used. Cows with a *corpus luteum* were treated with prostaglandin (150 µg D-Cloprostenol IM, Arsaprost, ARSA SRL®, Argentina) to effect luteolysis and to allow them to cycle, thereby increasing the proportion of cows cycling and inseminated during the first 21 days of the mating period. Ten days later, prostaglandin was injected to cows which were cycling but did not have a *corpus luteum* at the previous examination. Artificial insemination was for 75 days (from 1 October 2007) and 61 days (from 6 October 2008). The breeding season was shorter in year 2, to obtain a more compact calving pattern in the next season. Pregnancy diagnosis was by transrectal ultrasonography every 21 d, starting 28 days after insemination in those cows which did not return to oestrus.

Cows were culled on the basis of reproductive failure (i.e., failure to conceive) and health. Dry off (*i.e.*, termination of milking) policy was based on management decision rules similar to those suggested by Macdonald and Penno (1998). Thus, cows were dried 60 days before their expected calving date, or when their daily milk fat plus crude protein (MFP) production was less than 0.7 kg MFP/cow/day for two consecutive herd tests in autumn. In addition, cows with BCS less than 2.5 were dried after 9 April (*i.e.*, average lactation length of 8 months).

Grazing management

Electric fencing was used within paddocks to allocate a fresh strip of pasture after each milking. After the afternoon milking, cows were able to back graze the pasture remaining from the morning allocation. The grazing areas were available all year. No fertilisers were applied on pastures. Fifty kilograms of N/ha were applied to the sorghum at sowing.

Grazing rotation was optimised by grazing lucerne pastures as closely as possible to their optimum growth stage in all farmlets, which is 10% bloom in spring-summer and about 5 cm of re-growth from the crown in autumn/winter (Basigalup & Ustarroz, 2007).

The same herbage allowance (HA) was allocated to all the herds (kg herbage DM/herd/day). The HA (measured at 5 cm from ground level) per herd was calculated as twice the expected herbage DM intake (HDMI) for the low SR herd, to allow generous feeding to this treatment. Expected HDMI for the low SR herd was calculated by estimating maximum DM intake per cow (SCA, 1990), minus concentrate DM intake per cow, multiplied by the number of cows in the low SR herd. When HA available was lower than the desired value, sorghum silage was offered (from April to October, Figure 1) to achieve an optimum grazing rotation length while still keeping a HA of twice the expected HDMI for the low SR herd.

Pasture surplus to requirements was conserved as hay bales from November to February, and offered to cows of the same farmlet during periods of low pasture growth. A sample of pasture was collected before baling for DM determination and the bales were weighed. The amount of feed conserved in each paddock was calculated. Mechanical cutting (topping) of pasture residuals to 5.0 cm was completed after every grazing to maintain pasture quality, because it is the best practice for lucerne pastures (Basigalup and Ustarroz, 2007). Grazing management was determined on the basis of pre-grazing herbage mass (HM) estimated by two weekly samplings.

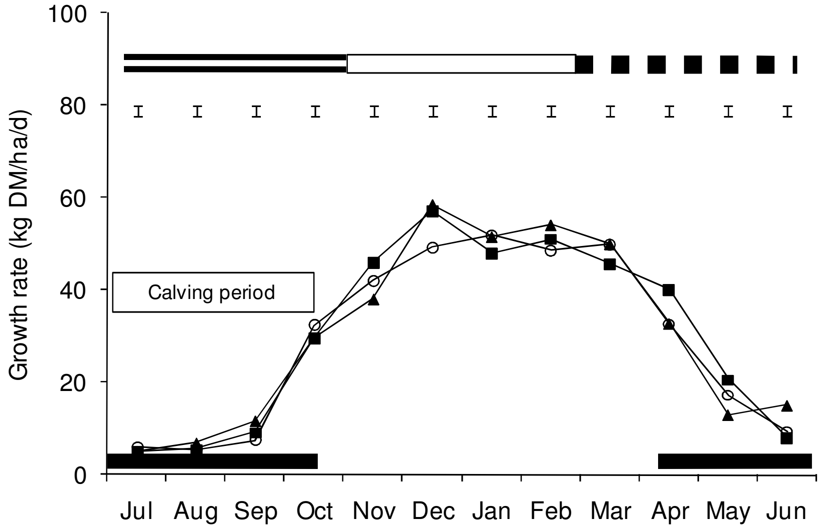
Feeding management

On the basis of previous annual pasture production of 10.5 t DM/ha/year and sorghum harvested for silage of 11 t DM/ha/year, annual allowances were approximately 5.7, 4.3 and 3.5 t DM per cow of pasture and 0.9, 0.7 and 0.6 t DM per cow of sorghum silage for the low, medium and high SR treatments, respectively. A common total amount of 1.8 t DM/cow of concentrates per year was offered to cows in all three treatments for each year. Therefore, expected total DM offered were 8.4, 6.8 and 5.9 t DM/cow/year for the low, medium and high SR treatments, respectively. For an expected average LW of 490 kg/cow, the expected comparative SR (kg LW/t of total DM offered; Macdonald *et al*., 2008) were 59, 73 and 84 kg LW/t of total DM offered for the low, medium and high SR treatments, respectively.

During the whole lactation, cows grazed pastures and were individually offered concentrates twice daily through an automatic feeding system during milking. The planned average amount of concentrate was 7.5, 5.0 and 3.5 kg DM/cow/day in early, mid and late lactation, respectively, in order to fully feed cows in the low SR treatment and to reduce the natural imbalance of proteins and carbohydrates caused by the consumption of lucerne pasture. A bloat preventative, ethoxylate alcohol and pluronic detergents (Bloker, Biotay, Argentina), was offered to cows fed with concentrate during milking in spring and autumn at a rate of 8 gs/100 kg LW. All cows were offered the same amount of concentrate per day.

Dry cows were offered 3 kg of concentrate per cow per day plus silage and hay *ad libitum*. Refusals of concentrates during milking were negligible. Hay and silage were offered in the paddock and rejections were not recorded. Sorghum silage with a high condensed tannin concentration was offered from April to October for cows in late lactation, dry period and early lactation, which is the period with highest bloat risk.

a)



b)

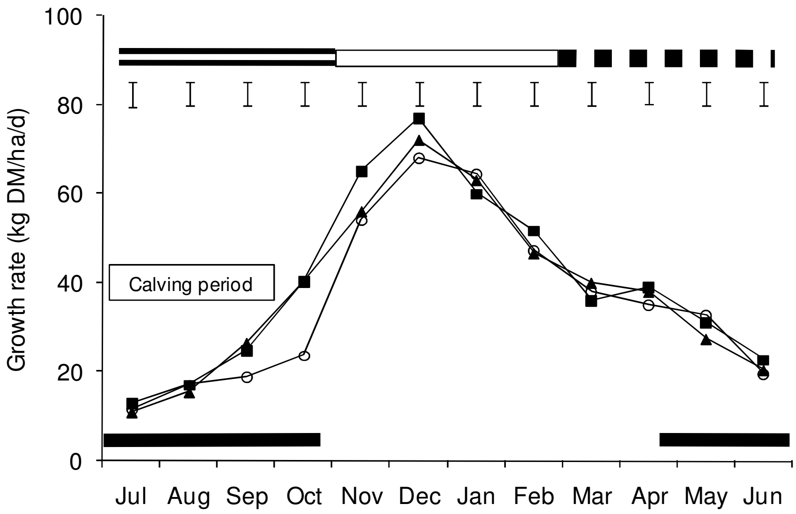


Figure 1 Seasonal pattern of pasture growth rate (a) 2007 to 2008 and (b) 2008 to 2009 for farmlet stocked at low (▲), medium (○) and high (▪). The lines in the top represent the amounts of concentrate offered to lactating cows, which were 9.1 (═), 4.9 (□) and 3.4 (■) kg DM/cow/day in the first year (a) and 7.2 (═), 4.7 (□) and 3.2 (■) kg DM/cow/day in the second year (b). Lines in the bottom (▬) represent periods in which high tannin sorghum silage and lucerne hay were offered. Vertical bars (I) are pooled SEM of pasture growth rate.

The concentrate ingredients were, on a proportional DM weight basis, for the whole experiment: wheat bran, 0.35; sorghum grain (high condensed tannins), 0.23; maize grain, 0.18; soya bean meal, 0.17; limestone flour, 0.03; mineral and vitamin mixture, 0.04. Chemical composition of the concentrates and silage is in Table 1.

Sward Measurements

Herbage mass

Pasture herbage mass (>5 cm above ground level) was measured twice weekly for all paddocks being grazed at the sampling dates. Pre-grazing herbage mass measurements were made from the next strip to be grazed (within the next 24 h) and the post-grazing measurements were made from the same strip, immediately after the cows left the paddock.

Herbage samples were collected with scissors from 8 randomly allocated quadrats of 50 × 50 cm. All clipped herbage from each square was collected, fresh weighed, sub-sampled (0.2 kg) and dried at 60°C until constant weight in a forced air oven for determination of DM content.

Botanical composition and plant density

The botanical composition of the herbage was determined every 2 weeks for each treatment. Twenty five samples of herbage of approximately 0.25 kg were collected randomly to a cutting height of 5 cm above ground level with scissors before grazing. Fresh herbage was immediately separated into its botanical constituents (*i.e.*, lucerne, clovers, weed, grasses, dead matter). Each constituent was dried in a forced air oven at 60°C until constant weight to determine botanical composition on a DM basis. Lucerne plant density was determined every 3 months on all paddocks by counting live plants contained in 8 randomly placed quadrats of 50 cm x 50 cm.

Feed quality

Herbage representative of that selected by cows on the low, medium, and high SR treatments was sampled every 2 weeks by a hand-plucking technique (Langlands, 1974), following close observation of cows to simulate grazing. Samples of concentrates, every two weeks, and silage, every month were also collected.

Sub-samples (0.2 kg) of lucerne pasture, sorghum silage and concentrates were oven dried at 60ºC in a forced air oven until constant weight to determine DM content and ground to pass a 1 mm screen using a Wiley mill (Arthur H. Thomas, Philadelphia, PA, USA). The analysis on sub-samples were: N (AOAC, 1990; # 976.05), ether extract (AOAC, 1990; # 920.39), acid detergent fibre (AOAC, 1990; # 973.18), sulphuric acid lignin (lignin(sa)) according to Robertson & Van Soest (1981), ash (AOAC, 1990; # 924.05), neutral detergent fibre (aNDF; Van Soest *et al.*, 1991) and *in vitro* DM digestibility (IVDMD; Tilley & Terry, 1963). Heat-stable amylase and sodium sulfite were used for aNDF determination and aNDF and ADF are expressed inclusive of residual ash.

Table 1 Chemical composition and DM digestibility of the concentrates and silage used, averaged over the two years (mean ± SD).

	Concentrate (Spring-summer)	Concentrate (Autumn-Winter)	Sorghum silage
DM (g/kg)	891 ± 6.2	898 ± 7.5	342 ± 28
DM composition (g/kg)			
CP	143 ± 31.6	174 ± 36.1	96 ± 5.6
aNDF	197 ± 43.3	262 ± 33.2	565 ± 33.8
ADF	63 ± 16.4	105 ± 24.3	308 ± 20.7
Lignin(sa)	15 ± 12.0	26 ± 10.9	65 ± 3.0
Ether extract	55 ± 5.3	47 ± 13.4	55 ± 5.5
Ash	62 ± 7.0	79 ± 18.3	62 ± 7.1
IVDMD	0.86 ± 0.301	0.84 ± 0.416	0.55 ± 0.291

CP, crude protein; aNDF, neutral detergent fibre; ADF, acid detergent fibre; lignin(sa),sulphuric acid lignin; IVDMD, *in vitro* dry matter digestibility.

Animal Measurements

Milk Production

Individual milk yields (kg/cow) were recorded fortnightly at two successive morning and evening milkings. Milk samples (50 ml/cow daily) were also collected at these milkings. A weighted compound sample was made and analyzed for fat, crude protein, lactose, and solids-not-fat by infrared methods (Milkoskan Model 4000, Foss Electric, DK- 3400, Hillørod, Denmark).

Live weight and body condition score.

The LW was recorded electronically every 3 weeks, using a portable weighing scale (Basculas Magris, HA 2000, Argentina). Body condition score was recorded on the same dates as LW using the 5 point BCS scale (1=thin to 5=obese) of Wildman *et al*. (1982).

Calculations

Pasture production, herbage intake and efficiency of grazing

Based on herbage mass (HM) determinations, the following parameters were calculated:

Pasture growth rate (PGR)

PGR (kg DM/ha/day) = Pre-grazing HM/days from previous grazing

Since pasture herbage mass was measured 5 cm above ground level, and mechanical cutting of pasture residuals to 5 cm was completed after every grazing, pre-grazing HM represented all the pasture grown between grazing.

Annual pasture production (APP)

APP (kg DM/ha/year) = ∑(Jul-Jun) Mean monthly PGR × days

Monthly PGR per paddock was calculated as the mean of all strips measured in each paddock per month. Mean monthly PGR was calculated as the mean of all paddocks for each farmlet.

Herbage allowance (HA)
HA (kg DM/cow/day) = Pre-grazing HM × daily grazing area / no. cows

Herbage DM intake (HDMI)
HDMI (kg DM/cow/day) = (Pre-grazing HM – post-grazing HM) × (daily grazing area / no. Cows)

Efficiency of grazing (EG; Hodgson, 1979)
EG (at a single grazing, g/kg) = (HDMI/cow / HA/cow × 1000)

Herbage growth between pre- and post-grazing samples was not accounted for because samples were within a 24 h period.

Lactation curves of milk, fat and protein yield,

Individual cow lactation curves for milk, fat and crude protein yields were obtained by fitting the exponential function of Wilmink (1987) to fortnightly measurements of these variables on each cow as:

$$y_t = a + be^{-0.05t} + ct$$

where: y_t represents yield (kg) at day t of lactation and e is the base of natural logarithm (2.718281828), while a, b and c are estimated parameters that define the height of the lactation curve, a, the initial phase of postcalving incline to peak, b, and the subsequent postpeak decline phase, c.

These parameters were estimated for each cow and for each lactation using the REG procedure of SAS (2003). Predicted milk yield values for each day of lactation, for each cow, were then obtained from the Wilmink function. Cumulative milk yield and milk components yields were calculated for each cow for each year, as the sum of yields from calving to the last actual day of lactation.

Lactation curves were also modelled with the incomplete gamma function of Wood (1967) and with a third order polynomial function. The goodness of fitness of these two functions and the Wilkmink function was compared using the Akaike information criteria, and the Wilmink function was selected as the best function.

Lactation curves of live weight and BCS

Lactation curves of LW and BCS were obtained for each cow and each lactation by fitting a regression polynomial of third order to actual LW and BCS measurements (every 3 weeks) during lactation as:

$$y_t = b_0 + b_1 t + b_2 t^2 + b_3 t^3$$

where: y_t represents LW or BCS at day t of lactation, and b_0, b_1, b_2 and b_3 are the regression coefficients of the polynomial equation. These parameters were estimated for each cow using the REG procedure of SAS (2003). Predicted LW and BCS for each day of lactation, for each cow, were then obtained from the polynomial equation. The LW and BCS changes during lactation were calculated as the difference between the predicted values from the polynomial equation for the last and first day of lactation.

Reproductive variables

The reproductive variables analysed were 21 days submission rate (*i.e.*, cows inseminated during the first 3 weeks of the breeding period/100 cows), the proportion of cows pregnant (cows pregnant/100 cows) at first service, and the proportion of cows pregnant by days 21, 42 and 84 from planned start of mating. Pregnancy rates were calculated using the last date of conception for those cows that presented embryonic deaths but conceived again during the mating season.

Statistical Analyses

All data were analysed using SAS (2003). All animal variables were analysed with cow as the experimental unit. Means and standard errors for each variable and each SR were obtained and comparisons among them were analysed using PROC MIXED for productive variables and the PROC GENMOD for reproductive variables after a logit transformation. The linear model included fixed effects of SR, parity, proportion of Holstein genes (fitted as co-variable), the random effect of year and the random effect of cow nested within treatment. Using the Akaike's information criterion, a compound symmetric error structure was determined as the most appropriate residual covariance structure for autocorrelated repeated measures on the same cow.

All pasture and intake variables measured in individual paddocks were analysed using PROC MIXED, with paddock as the experimental unit and with repeated measures in the same paddock. The model included fixed effects of SR, season and year of experiment, and random effects of paddock nested within treatment. Cumulative pasture production, and cumulative feed consumption were estimated for each paddock, annually, and analysed using PROC MIXED, with SR as the fixed effect and year as the random effect. Monthly PGR were analysed using PROC MIXED, with the fixed effects of SR and the random effects of paddock nested within treatment. For both animal and pasture variables, mean differences between treatment effects were declared significant at a probability <0.05.

RESULTS

In general, no serious animal health issues from year round grazing of legume pastures were observed. The use of a bloat preventative added to the concentrates effectively precluded bloat problems during the 2 years of the experiment. The exception was that one cow died after a bloat event in spring 2007. Reasons to replace cows were reproductive failure (19), mastitis (5) and lameness (6).

Pasture quality, persistence and botanical composition

The hand-plucked samples collected at the SR did not differ in any parameter of pasture quality evaluated (Table 2), and there was no difference in the botanical composition of pasture (Table 2).

Lucerne plant density over the 2 years did not differ between SR treatments and were 28 ± 2.8, 32 ± 2.8 and 33 ± 2.5 plants/m^2 for the low, medium and high SR paddocks, respectively. Initial plant density (August 2007) was 43 ± 17.8, 46 ± 14.7 and 50 ± 14.7 plants/m^2 and final plant density (June 2009) was 22 ± 1.5, 20 ± 1.9 and 23 ± 1.9 plants/m^2 for the low, medium and high SR paddocks, respectively. There were no effects of SR on either initial or final plant density.

Table 2 Effects of stocking rate on chemical composition and botanical composition (g/kg DM) of fortnightly pasture samples averaged over 2 years.

	Stocking rate (cows/ha)			SEM
	1.6	2.1	2.6	
Chemical composition[1]				
DM (g/kg)	209	216	208	3.9
DM composition (g/kg DM)				
CP	237	223	229	7.7
aNDF	444	457	447	118.3
ADF	233	249	238	7.3
Botanical composition (g/kg)[2]				
Lucerne	783	794	746	185.4
Clover	65	56	76	155.0
Weeds and grasses	105	115	132	154.7
Dead matter	47	35	46	7.3

There were no differences due to stocking rate for any response parameter (*i.e.*, P>0.05).
[1] Pasture quality samples were hand-plucked.
[2] Botanical composition samples were cut to 5 cm above ground level.
CP, crude protein; aNDF, neutral detergent fibre; ADF, acid detergent fibre.

Weather and grass production

Annual rainfall was lower than the average at 956 mm for both years, being 803 and 674 mm in the first and second year, respectively. However, pasture production was slightly higher than expected (from previous records in the same farm), for both years. During the 2 years, average monthly measurements of water table (*i.e.*, upper surface of groundwater) at INTA Research Station indicated that water table was at a depth of 1.74 ± 0.72 m.

Total pasture production and pre-grazing herbage mass were not affected by SR (Table 3). Pasture production from October to March inclusive was 0.73 of annual pasture production. The PGR ranged from less than 10 kg DM/ha/day in winter to 80 kg DM/ha/day in spring/summer (Figure 1). Average silage harvested was 11.6 t DM/ha per year. All silage harvested was used during the experiment. Thirteen lucerne hay bales (7.5 t DM in 2 years) were bought in for the medium SR farmlet to feed the dry cows. The annual amount of concentrates offered were similar to planned. The amounts of concentrates offered in early lactation were higher than planned for both years because of the slow PGR in this period (Figure 1).

Feed intake and milk yield

Pasture available per cow was 6.6, 4.7 and 4.1 t DM/cow/year and actual comparative SR were 58, 67 and 75 kg LW/t total DM offered for low, medium and high SR, respectively. These latter values were slightly lower than planned due to higher than expected DM production from pasture. Effects of SR on intake of feeds are in Table 3, while effects of SR on milk yield are in Table 4.

The HA (kg DM/cow/day) decreased with increasing SR ($P<0.05$), as planned. The HDMI and total DM intake per cow were reduced at higher SR ($P<0.05$), but this reduction was only significant in mid lactation. A tendency ($P=0.10$) for reduced total DM intake as pasture plus supplements with increasing SR also occurred in late lactation. The EG increased with increasing SR ($P<0.05$), with an increase of 143 g/kg DM from low to high SR.

Table 3 Effects of stocking rate on pasture production, efficiency of grazing (EG) and feeds intake for farmlets at the three stocking rates, averaged over the 2-year period. All pasture measurements were at a cutting height of 5 cm above ground level.

	Stocking rate (cows/ha)			SEM
	1.6	2.1	2.6	
Per hectare of pasture/year[1]				
Annual pasture production (t DM)	12.1	11.5	12.2	2.72
Pre-grazing herbage mass (t DM)	1.7	1.6	1.8	0.22
Pasture conserved as hay (t DM)	1.4a	0.4b	0.9a	0.15
Pasture consumed (t of DM)	5.8a	7.2b	8.2c	0.24
Per cow/year				
Pasture consumed[2] (kg DM)	3150	2916	2775	78.8
Silage and hay consumed[3] (kg DM)	1130	1145	965	57.4
Concentrates consumed[4] (kg DM)	1778	1785	1780	33.6
Per cow/day of lactation				
Herbage allowance (HA; kg DM)	16.9a	13.5b	12.2b	0.54
Herbage intake[5] (kg DM)				
Early lactation	6.6	5.4	6.2	0.47
Mid lactation	13.5a	12.9a	11.6b	0.42
Late lactation	10.8	11.1	10.3	0.49
Efficiency of grazing[6] (EG; g/kg)	620a	718b	763b	142.1
Silage and hay intake (kg DM)	2.1a	2.2a	1.6b	0.36
Concentrates intake (kg DM)	5.3	5.3	5.3	0.87
Total intake (kg DM)				
Early lactation	17.8	17.1	16.9	0.28
Mid lactation	18.1a	17.8a	16.2b	0.23
Late lactation	17.3	16.8	15.4	0.53

[a, b and c] For the same row, means with different subscripts differ (P<0.05).
[1] Pasture area was 0.86 of total farmlet area.
[2] Calculated as kg DM/cow/day consumed during lactation times days in milk.
[3] Calculated as kg DM/cow/day consumed during lactation times days in milk plus 427, 455 and 427 kg DM/cow offered during dry period for low, medium and high SR, respectively.
[4] Calculated as kg DM/cow/day consumed during lactation times days in milk plus 183, 195 and 183 kg DM/cow offered during dry period for low, medium and high SR, respectively.
[5] Herbage removed at grazing.
[6] Calculated using the sward cutting method (Herbage DM intake ÷ herbage allowance × 1000) (Hodgson, 1979).

Table 4 Lactation length, annual milk production per cow and per hectare, average milk composition, LW and BCS at the three stocking rates, averaged over 2 years.

	Stocking rate (cows/ha)			SEM
	1.6	2.1	2.6	
Lactation length (d)	304	300	304	6.9
Annual production/cow (kg)				
Milk	7104	6503	6743	389.2
Fat	273	258	263	11.9
Crude protein	254a	230b	241ab	11.0
Annual production/ha[1] (kg)				
Milk	11366a	13807ab	17206b	914.3
Fat	437a	548ab	671b	30.8
Crude protein	406a	488ab	615b	28.3
Milk composition (g/kg)				
Fat	38.9	40.3	39.3	0.84
Protein	35.9	35.7	35.8	0.60
LW (kg) and BCS (1 to 5)				
Calving LW	472	472	465	11.6
Calving BCS	2.59	2.68	2.49	0.069
Minimum LW during lactation	457	460	453	7.8
Minimum BCS during lactation	2.35	2.43	2.31	0.062
LW change during lactation	54	52	47	6.1
BCS change during lactation	0.18	0.04	0.29	0.196

[a, b and c] For the same row, means with different subscripts differ (P<0.05).
[1]Total farmlet area is pasture area plus silage area.

Silage and hay DM intake per cow were lower at high SR compared to low and medium SR (P<0.05). Concentrate DM intake was the same for cows in all treatments. Total DM intake as pasture plus supplements per cow declined with increasing SR, but only in mid lactation (P<0.05). Pasture consumed per ha of pasture increased by 2.4 t

DM/ha/year (*P*<0.05) and concentrates consumed per ha total increased by 1.8 t DM/ha/year from low to high SR.

Annual milk, fat and crude protein yields per cow and lactation length did not differ among treatments, but a trend (*P*=0.063) toward lower milk production at higher SR occurred (Figure 2 and Table 4).

Live weight and body condition score

No differences between treatments occurred for LW or BCS change during lactation (Table 4). The BCS was relatively low at calving for all treatments (*i.e.*, <2.7). The BCS and LW increased from calving to the end of lactation in all treatments, but there were no differences for initial (calving) and final (end of lactation) BCS and LW.

Lactation profiles

Peak milk yield had a trend to a decrease (*P*=0.07) at higher SR (Table 5 and Figure 2), in agreement with the trend to lower annual milk yield per cow at higher SR. The average R^2 obtained from fitting the Wilmink function to actual data were 0.77 for milk, 0.77 for protein and 0.75 for fat yield. There were no treatment differences for any of the parameters of the Wilmink function (Table 5).

Reproductive performance

Stocking rate had no effect on any of the reproductive variables measured (Table 6). Average submission rate was 77 cows inseminated during the first 3 weeks of the breeding period/100 cows, average pregnancy at first service was 47 cows pregnant/100 cows, and average pregnancy rates were 42, 66 and 80 cows pregnant/100 cows by day 21, 42 and 84, respectively.

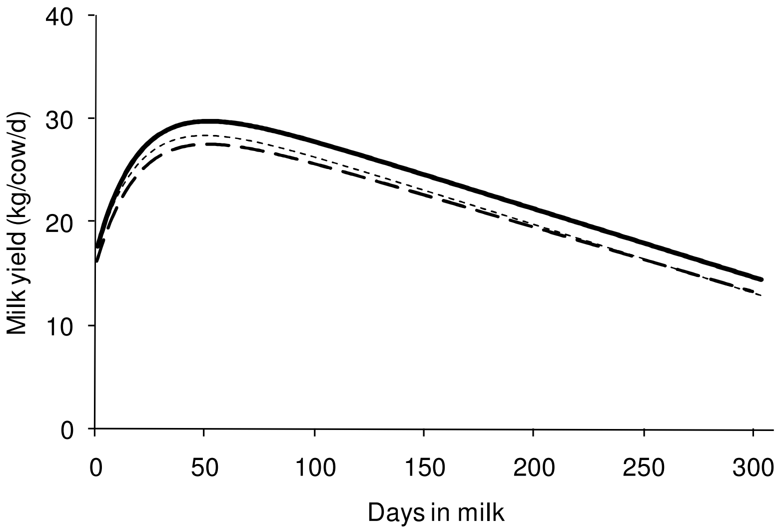


Figure 2 Effects of stocking rate on the lactation profile for milk yield (kg/cow/day). Stocking rates were 1.6 (▬), 2.1 (— —) and 2.6 (- -) cows/ha. Data averaged over the 2 years of the experiment. There were no differences between lactation curves (*i.e., P*>0.05).

Table 5 Milk yield parameters estimated with the exponential function of Wilmink (1987), and predictions of peak milk yield and days in milk (DIM) to peak at the three stocking rates, averaged over 2 years.

	Stocking rate (cows/ha)			SEM
	1.6	2.1	2.6	
a[1]	34.55	31.99	33.03	0.999
b[1]	-17.6	-16.4	-16.2	5.94
c[1]	-0.066	-0.062	-0.066	0.0071
Peak milk yield (kg/cow/day)	31.0	28.4	28.9	0.83
DIM to peak (days)	46	45	43	5.2

There were no differences due to stocking rate for any response parameter (*i.e.*, *P*>0.05).
[1]Estimated parameters of the Wilmink function relating to the height of the lactation curve (a), the initial phase of postcalving incline to peak (b), and the subsequent postpeak decline phase (c).

Table 6 Effects of stocking rate on the 21 days submission rates, the proportion of cows pregnant at first service (Pregnant 1st), and the proportion pregnant by day 21 (Pregnant 21 d), 42 (Pregnant 42 d) and 84 (Pregnant 84 d) from planned start of mating. Data averaged over 2 years.

	Stocking rate (cows/ha)		
	1.6	2.1	2.6
Submission rate[1]	75 (55-88) [2]	80 (67-89)	75 (61-85)
Pregnant[3] 1st	46 (29-63)	41 (29-55)	54 (39-68)
Pregnant[3] 21 d	38 (23-56)	45 (31-59)	42 (28-57)
Pregnant[3] 42 d	70 (51-83)	67 (53-78)	62 (47-75)
Pregnant[3] 84 d	78 (62-89)	85 (73-92)	77 (64-86)

There were no differences due to stocking rate for any response parameter (*i.e.*, $P>0.05$).
[1]Cows submitted for insemination during the first three weeks of the breeding period/100 cows.
[2] 95% Confidence interval in brackets.
[3] Expressed as cows pregnant/100 cows.

DISCUSSION

This study was a 2-year comparison using a whole farmlet system design. It explored effects of SR on production of lucerne pasture, its quality, utilisation and persistence, together with effects of SR on animal performance and productivity per hectare using a whole system approach. This was effected using year round grazing of lucerne based pastures. Bloat was effectively controlled during the 2 years using a bloat preventative added to concentrates. In addition, condensed tannins in the sorghum silage and sorghum grain included in the concentrate may have contributed to low bloat (Reid *et al*., 1974).

Previous studies in Argentina have investigated partial effects of SR but were either short term (Alvarez *et al*., 2007) or simulation studies (Comerón *et al*., 1995; Comeron & Schilder, 1997; Romero *et al*., 1995). While there are comprehensive published studies of effects of SR on dairy systems in other countries, they all used grass based pastures (Dillon *et al*., 1995; Fales *et al*., 1995; Macdonald *et al*., 2008; Valentine *et al*., 2009) rather than lucerne.

The experiment was designed to allow for generous feeding of cows on the low SR treatment, by using high HA plus supplements, in order to achieve high DM intake and high milk yield per cow in this treatment. The medium and high SR treatments were designed to explore changes in the pasture, cows and system as feed demand per hectare was increased while pasture and silage offered per hectare remained constant. Farmlets were balanced in regards to cows and paddock characteristics before the experiment. Further farmlet experiments should be carried out to confirm results obtained in our experiment, mainly to test the robustness of these results under changes in rainfall and temperature that occur for different years.

Pasture production, quality and persistence

Pasture production was higher than expected, despite rainfall being lower than average. This may be because lucerne is able to grow roots deeper into the soil than traditional crops and pastures (Ward *et al.*, 2006), extracting water from 100 mm or deeper (Mundy *et al.*, 2006). In addition, capillary contribution (between 15% and 25% of crop water use) from the water table has been reported for lucerne in Argentina (Dardanelli & Collino, 2002), and possibly an important water contribution from this source occurred in our experiment, since water table was 1.74 ± 0.72 m.

A reduction in lucerne plant density was expected at higher SR, as a consequence of pugging damage resulting from increased number of animals per unit area at higher SR. Pugging, described as the formation of hoof prints that are caused by pressure on soil under wet conditions, can cause direct damage to pasture (Nie *et al.*, 2001). Probably, the low rainfall prevented pugging damage. Absence of an effect of SR on pasture production is consistent with the absence of an effect of SR on lucerne plant density.

Differences in pasture production were prevented by optimal grazing management which allowed lucerne pasture to be grazed at an optimum stage in all treatments (*i.e.*, once carbohydrates reserves were replenished). Re-growth of lucerne pastures is almost independent of residual leaf of lucerne plant, since the energy used for re-growth comes from reserve carbohydrates in the crown and roots, and this depends on frequency of grazing (Basigalup & Ustarroz, 2007). Consistent with our results, an experiment with steers grazing lucerne pasture found a difference in DM production between high and low SR, only in one of four years (Popp *et al*., 1997b).

In contrast to lucerne pastures, perennial ryegrass pastures are affected strongly by residual leaf area after grazing for re-growth, thus periodic defoliation and relatively low residuals are required to renew photosynthetic efficiency and pasture quality. This characteristic may explain the increment in pasture grown as SR was increased in a farmlet trial with dairy cows grazing ryegrass based pastures (Macdonald *et al*., 2008), in which grazing residuals associated with more green leaf and higher pasture quality were lower at higher SR.

Quality of lucerne declines from its top to bottom (Basigalup & Ustarroz, 2007). Given the vertical structure of lucerne swards, progressive defoliation of the lucerne sward horizons should result in a pasture with higher stem to leaf ratio of lower nutritive quality (Popp *et al*., 1997a). Since EG was higher at higher SR in our study, deeper sward horizons were grazed by cows at higher SR, and therefore, a lower quality of pasture consumed at higher SR was expected.

However, pasture quality, as analysed in hand-plucked samples, remained constant in all treatments. Two explanations support this absence of difference among treatments. First, from visual observations before taking the simulated grazing samples (*i.e.*, hand-plucking), the proportion of stem in the residual herbage mass appeared to be higher and few leaves remained at the higher SR. This means that stripping of leaves with higher quality than stems by grazing animals occurred, particularly at higher SR. In addition, mechanical cutting of pasture residuals to 5 cm was completed after every grazing which removed effects of SR on quality of the pasture on offer at the next grazing.

Higher pasture quality ($P<0.05$) at higher SR was measured in samples clipped (*i.e.*, pasture on offer) from lucerne pastures stocked with steers, but no differences were measured when pasture samples were collected from esophageal fistulated steers (Schlegel *et al*., 2000), to represent pasture consumed. This indicates that bovines are able to select a higher quality diet than the average on offer, as reported in several studies with cattle grazing lucerne (Popp *et al*., 1999; Schlegel *et al*., 2000). In future studies, measurement of the ratio of stem to leaf for pre and post-grazing herbage mass of lucerne pasture would help to explain effects of SR on the quality of the pasture consumed.

For whole lactation farmlet studies with ryegrass pastures, consistent reductions in aNDF (Macdonald *et al*., 2008; Valentine *et al*., 2009), increases in CP content (Valentine *et al*., 2009) and increases in digestibility and metabolisable energy content of pastures (Macdonald *et al*., 2008) were reported at higher SR. These results are consistent with expectations for ryegrass based pastures, in which a higher SR results in lower pasture residuals and more green leaf proportion, associated with higher pasture quality.

Indicators of long term sustainability, such as physical soil properties or soil nutrient balance, were not measured. This is a short-term experiment and therefore, the effects of SR on those indicators would be expected to be small. However, no fertilisers were applied to pastures to reduce the risk of nutrient leaching and the persistence of lucerne plants did not differ among treatments, suggesting that soil properties were not critically altered as SR increased. Valentine *et al*. (2009), based on nutrient balance results from a farmlet study, suggested a sustainable upper level of SR at 2.5 dairy cows/ha for dry land pastures in Australia, in which 100 kg N/ha/year were applied.

Feed intake and milk yield

Results from studies which investigated effects of SR on milk yield per cow have been equivocal. However, common factors such as feed intake at different stages of lactation and use of supplementary feeds, consistently account for differences in effects of SR on milk yield per cow.

The HDMI and total DM intake per cow were lower at higher SR, but only in mid lactation. The high proportion of supplements used to compensate for low PGR in early lactation (Figure 1) reduced potential differences in DM intake between treatments in this period.

Previous farmlet studies explored the effects of SR. Ninety-four cows were used in a 3 years experiment of Macdonald *et al.* (2008) in New Zealand, 180 cows in a 4 years experiment of Valentine *et al.* (2009) in Australia, 75 cows were used in a 3 years experiment of Dillon *et al.* (1995) in Ireland, 48 cows were used in a 2 years experiment of Fales *et al.* (1995) in US and 182 cows were used in a 3 years experiment of Macdonald *et al.* (2008) in New Zealand.

Milk yield per cow per lactation showed only a trend toward lower milk yield at higher SR. This is consistent with Fales *et al.* (1995), who found no effect of SR on milk yield per cow, and Dillon *et al.* (1995), who showed only a small effect of SR on milk yield per cow. A common factor in our and in the latter studies is that feed restriction of higher SR in early lactation was reduced by supplementation. Feed restriction in early lactation was removed by feeding concentrates in proportion to milk production (0.25 kg of grain/kg of milk) in Fales *et al.* (1995) and by delaying the calving date by 7 weeks in the high SR treatments in Dillon *et al.* (1995).

In contrast, as discussed in Chapter 2, milk yield per cow decreased at higher SR in a farmlet system study with cows offered pasture only, or pasture plus only a small amount of concentrates (Macdonald *et al.*, 2008), but DM intake per cow in early lactation was reduced at higher SR. Similarly, another farmlet study (Valentine *et al.*, 2009) reported decreases in DM intake and milk yield per cow as SR increased, in the first 2 year of the experiment, when purchased supplements were not enough to remove feed restrictions during lactation, but there were no differences in the last 2 year of the experiment when increased amounts of purchased supplements were used to compensate for the reduction in pasture intake at higher SR. Similar results were reported by Macdonald (1999). In all the aforementioned studies, including our study, when enough high quality supplements were offered during early or early and late lactation, negative effects of higher SR (*i.e.*, lower HA and shorter lactations) were removed, and no differences in milk yield per cow occurred.

A further explanation for the lack of effect of SR on milk yield per cow in our study is that the diet of cows comprised more than 550g/kg of lucerne in all treatments. This may have created a nutritional imbalance, due to the natural excess of degradable N relative to readily fermentable energy in lucerne pastures, limiting milk yield, particularly in the low and medium SR cows. Excess of soluble N is excreted via the urine, which reduces the efficiency of energy utilisation.

Yields of milk, fat and crude protein per ha increased as SR increased, consistent with previous farmlets studies (Fales *et al.*, 1995; Macdonald *et al.*, 2008; Valentine *et al.*, 2009), and can be attributed to higher pasture utilisation and to the larger amount of concentrates eaten per ha at higher SR in our study. It is worthy of note that crossbred cows were used in the present study, and probably a different response to SR would have occurred with Holstein-Friesian cows (Auldist *et al.*, 2007).

Live weight and body condition score

In our experiment, as in Fales *et al.* (1995) and in Valentine *et al.* (2009), supplementation per hectare was increased at higher SR, and this prevented higher losses of LW during lactation, and lower LW, for cows at the higher SR.

Losses of LW during lactation, of 22 kg or more for an increase of 1 cow/ha, have been reported in farmlet experiments that either did not increase supplementation per hectare as SR increased (Macdonald *et al.*, 2008) or included high SR up to 8.6 cows/ha (King & Stockdale, 1980). Comparison of changes in milk yield or LW per unit increase in SR in different experiments should be done only after distinguishing those studies that offered supplements from those that did not.

Changes in BCS throughout lactation were very small in all three SR treatments, with the decrease in BCS from calving to the minimum BCS during lactation being only 0.25 or less. This agrees with Roche *et al.* (2007), who reported lower BCS loss in early lactation with decreasing calving BCS. The BCS gain from this minimum BCS to end of lactation was also small, 0.5 or less, in agreement with Berry *et al.* (2002), who found that cows losing less BCS in early lactation tend also to gain less BCS in late lactation. However, care must be taken when comparing BCS results from different studies, because BCS is a subjective parameter.

Reproductive performance

Our results agree with previous studies (Dillon *et al.*, 1995; Washburn *et al.*, 2006; Macdonald *et al.*, 2008), which found no effect of SR on reproductive performance. In our study, the lack of differences in reproductive performance is consistent with the lack of differences in feed intake per cow among treatments in early lactation. However, more cows would have been required to make any firm conclusions on the effect of SR on reproductive efficiency.

Under pasture based systems in Australia and New Zealand, submission rates are close to 80 cows inseminated during the first three weeks of the breeding period/100 cows, 55 to 65 cows pregnant/100 cows at first service and 90 cows pregnant/100 cows by the end of the seasonal breeding programme (McDougall, 2006). Submission rates were similar to those systems in all treatments in our study, but the proportion of cows pregnant at first service and final pregnancy rate were lower in our study.

CONCLUSIONS

To our knowledge, this is the first farmlet experiment that explored effects of SR using dairy cows grazing lucerne based pastures. Crossbred cows in a seasonal spring calving system grazing lucerne pastures and offered moderate amount of concentrates produced almost three times more milk per ha (higher SR treatment) than the average production of Argentine dairy farms.

Higher SR had no effects on pasture production, pasture quality, pasture persistence and botanical composition. The EG was increased at higher SR and this partially compensated for the lower HA at higher SR. Additionally, use of supplements contributed in compensating for the lower HA of the high stocked cows and therefore, theoretical reductions in milk yield per cow at higher SR were prevented and only a tendency to lower milk yield per cow was observed.

As SR increased from 1.6 to 2.6 cows/ha, pasture consumed increased by 2.4 t DM/ha/year, concentrates consumed increased by 1.8 t DM/ha/year and milk yield increased by 5840 kg/ha/year. Results indicate that large increases in milk production per ha from lucerne based pastures are realistically achievable in Argentina by increasing SR while feeding a fixed amount of supplements per cow per year. Further whole-farm research should be conducted for Argentine dairy systems to explore higher levels of SR and different cow genotypes, as well as possible environmental effects of SR.

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Chapter 4

Effect of herbage allowance on dry matter intake, milk yield and grazing behaviour of crossbred Holstein-Jersey dairy cows grazing lucerne pastures in early lactation

J. Baudracco[1,3], E.A. Comeron[2]; N. Lopez-Villalobos[1], L.A. Romero[2], D. Scandolo[2] M. Maciel[2], Barry, T.N[1], and C.W. Holmes[1]

[1] *Massey University, Institute of Veterinary, Animal and Biomedical Sciences, Private Bag 11-222, Palmerston North, 5301, New Zealand.*

[2] *Instituto Nacional de Tecnología Agropecuaria (INTA), AIPA, Ruta 34 Km 227, (2300) Rafaela, Santa Fe, Argentina.*

[3] *Facultad de Ciencias Agrarias, Universidad Nacional del Litoral, Kreder 2805, Esperanza, CP: S3080HOF, Argentina.*

Submitted to Animal Feed Science and Technology

ABSTRACT

The objectives of this study were to research the effects of herbage allowance (HA) on dry matter (DM) intake, milk yield and grazing behaviour of dairy cows grazing lucerne (*Medicago sativa L.*) pastures, and to compare estimates of herbage DM intake using an indigestible intake marker (LIPE®) versus estimates of herbage DM intake using the animal performance method, which is based on the metabolisable energy requirements for lactation, live weight change and maintenance of the cows and the metabolisable energy content of the herbage.

Twenty-six spring-calving crossbred Holstein-Jersey dairy cows (0.49 Jersey genes, 84 days in milk) were balanced and randomly assigned to either the low or the high HA treatment between 19 and 26 September 2008. Cows were offered either 10.0 (low HA) or 14.5 (high HA) kg DM/cow/day of lucerne pastures at grazing and were offered Sorghum (S*orghum bicolor*) silage (3.7 kg DM/cow/day) and concentrates (5.6 kg DM/cow/day). Decreasing HA decreased herbage DM intake measured with LIPE® by 1.1 kg/cow/day (P<0.05), increased the efficiency of grazing (herbage consumed/herbage allowance × 1000; g/kg DM) by 210g/kg (P<0.01), increased silage DM intake by 0.3 kg/cow/day (P<0.05), and decreased total metabolisable energy intake by 12 MJ ME/cow/day (P<0.05), but did not affect total DM intake (P>0.05). The cows on the lower HA treatment produced less milk (-4.1 kg/cow/day) (P<0.05) and grazed 26 minutes/day longer (P<0.05) than cows at the high HA. Herbage DM intake measured with LIPE® was positively correlated with estimates of herbage DM intake from the animal performance (R=0.65, P<0.01) method. This study showed that high efficiency of grazing can be achieved on lucerne pasture, and showed a moderate correlation between herbage DM intakes estimations with LIPE® and with the animal performance method.

INTRODUCTION

In countries where the price of milk paid to farmers is low, such as Argentina (Hemme, 2009), production costs need to be low, and this can be achieved by efficiently grazing pastures, the cheapest source of feed. In this situation, stocking rate, which is closely related to herbage allowance, is a major factor determining the efficiency of the system (McMeekan & Walshe, 1963; King & Stockdale, 1980).

Herbage dry matter (DM) intake per cow and individual animal performance are reduced when stocking rate is increased, *i.e.*, herbage allowance decreases (Macdonald *et al.,* 2008). Lucerne (*Medicago sativa L.*) pasture is the main source of feed for dairy cows in Argentina (Collino *et al.*, 2005), in combination with concentrates and conserved roughages. The relationship between herbage allowance (HA) and herbage DM intake (HDMI) was studied for dairy cows grazing lucerne pastures in Argentina (Comerón *et al.*, 1995; Romero *et al.*, 1995; Alvarez *et al.*, 2006), but in these experiments, HDMI was estimated for a group of animals from DM disappearance in the sward, using the sward cutting method (Meijs *et al.*, 1982).

Several techniques have been developed to estimate individual animal intake at grazing (Reeves *et al.*, 1996). These techniques estimate intake by measuring or estimating faecal output and digestibility, and most of them utilise external markers added to the diet or internal indigestible markers that are endogenous, *i.e.*, a constituent of the diet (Lippke, 2002). Recently, an external intake marker was developed from a purified enriched lignin (LIPE®) extracted from *Eucalyptus grandis* (Rodriguez *et al.*, 2007). The intake marker LIPE®, which is a modified *hydroxyphenylpropane*, has proven to be a reliable estimator of faecal output for several animal species (Rodriguez *et al.*, 2007; Saliba *et al.*, 2006; Saliba *et al.*, 2003). Therefore, LIPE® is promising as an intake marker to evaluate individual HDMI, based on total faecal output estimations and feed digestibility.

The objectives of this study were: i) to compare DM intake, milk yield, feed conversion efficiency (FCE) and grazing behaviour of cows grazing lucerne pastures at low or high HA, and ii) to compare the estimates of HDMI using either the LIPE® method or the animal performance method, which is based on the metabolisable energy requirements for lactation, live weight (LW) change and maintenance of the cows and the metabolisable energy content of the herbage.

MATERIALS AND METHODS

Experimental design

The experiment was carried out at Instituto Nacional de Tecnología Agropecuaria (INTA), Rafaela, Argentina, at latitude 31.11S, longitude 61.33W and altitude 99m. This study started on 19 September (Day 1) and finished on 26 September (Day 8) 2008. Twenty-six crossbred Holstein-Jersey dairy cows were temporarily withdrawn from a 2-year farmlet experiment which explored the effects of stocking rates of 1.6, 2.1 and 2.6 cows/ha on farm efficiency, from 1 July 2007 (Baudracco *et al*., 2011). Thirteen cows from the high SR farmlet were allocated to the Low HA treatment (10.0 kg DM per/cow/day) and 13 cows from the to the low SR farmlet were allocated to the High HA treatment (14.5 kg DM per/cow/day).

In the present study, cows grazed pasture in two herds, *i.e.*, low and high HA, and were offered concentrate and silage individually. Two weeks prior to the experimental period, each herd was offered the same diet than that used in the experimental period. The present experiment was approved by Massey University Animal Ethics Committee: MUAET protocol 08/49.

Animals

Cow groups were balanced on the basis of days in milk (84 ± 14d), lactation number (2.5 ± 0.64), proportion of Jersey genes (0.49 ± 0.16) with a range from 0.75 Holstein to 0.75 Jersey genes in individual cows, LW at calving (455 ± 56 kg) and a feed conversion efficiency (FCE) index (1.13 ± 0.42 g milksolids (fat plus crude protein) per kg DM). The FCE index was calculated from the previous lactation for each cow, as grams of milksolids (MS) produced per kilogram of DM consumed (Kolver, 2007). Dry matter consumed was estimated on the basis of milksolid yields, LW records, and ME requirements for milk, maintenance and pregnancy. On Day 1 of the experiment, body condition score averaged 2.5 ± 0.17 measured on a 5-point BCS scale (Wildman *et al.*, 1982). A regression polynomial of third order was fitted to actual LW measurements for each cow during lactation. Predicted LW for each day of lactation, for each cow, were then obtained from the polynomial equation. More detail is given under the section named ‘live weight changes’ below.

Feeding management

Cows were kept in two different herds and each herd grazed a different paddock of lucerne (*Medicago sativa* L.) pastures. Electric fencing was used within paddocks to allocate a fresh strip of pasture for each herd after each milking (4:30 h and 15:00 h) to give target HA of 10.0 and 14.5 kg DM per/cow/day (measured 5 cm above ground level) for the low and high HA, respectively.

At 9:00 h, cows were retrieved from pasture for LIPE® dosage and faecal sampling. After faecal sampling, cows were offered 3.74 ± 0.15 kg DM/cow/day of Sorghum silage (*Sorghum bicolour*) in individual plots of 3m x 5m, divided by electric fences. Cows were removed from these plots after all cows in the treatment had stopped eating silage. Each cow received 2.8 ± 0.12 kg DM of concentrate twice daily at milking, individually through an automatic feeding system. Silage DM offered and rejected and concentrate DM offered to each cow were weighed from Day 4 to Day 8. Concentrate DM rejected was considered to be nil.

Animal measurements

LIPE® dosing, faeces sampling and analysis

Cows were dosed once a day (from 9:00 h) with a gelatine capsule containing 500 mg of LIPE® for 7 consecutive days, starting on Day 1 and finishing on Day 7. To make sure that capsules were not regurgitated, animals were observed individually for three minutes after being dosed with the LIPE® capsule, and careful inspection of the yard in which the cows were kept was performed for 20 minutes after dosing.

Faecal samples were taken from the rectum of each cow once-a-day (from 9:00 h) for five consecutive days, from Day 4 of LIPE® dosage until Day 8. All faecal samples (5 samples × 26 cows) were processed and analyzed individually. Faecal samples were weighed and dried immediately after sampling at 60ºC in a forced air oven until constant weight to determine DM content. Samples were ground to pass through a 1 mm screen using a Wiley mill (Arthur H. Thomas, Philadelphia, PA, USA) and stored for analysis. Dry matter was also determined using an oven at 105ºC until constant weight.

Faecal samples of 2 mg and 300 mg of powdered Potassium bromide (KBr) were ground in an agate mortar and homogenised for 20 minutes. Pressed pellets were then obtained after 1 minute at constant pressure. Concentration of LIPE® in faeces was analysed by infrared spectroscopy using an infrared spectrometer VARIAN 800 FT-IR (Varian BV, Middelburg, The Netherlands). Standard calibration curves for LIPE® were prepared by measuring the absorbance of five different concentrations of LIPE® to produce a regression equation relating concentration to absorbance, which had an R^2 higher than 0.95. This equation allowed calculations of LIPE® concentration by measuring absorbance in faecal samples.

Milk production

Milk yields (kg/cow) were recorded daily at the two successive morning and evening milkings during the five days in which faecal samples were collected (Day 4 to Day 8). Milk samples (50 mL per cow, daily) were also collected at these milkings. A weighted compound sample was made and analysed for fat, crude protein and lactose by infrared methods (Milkoskan Model 4000, Foss Electric, DK-3400, Hillørod, Denmark).

Live weight and body condition score.

The LW was recorded electronically on two consecutive days immediately before and after the experimental period, using a portable weighing scale (Basculas Magris, HA 2000, Argentina). Body condition score was recorded on the same days, using the 5-points BCS scale (1 = thin to 5 = fat) proposed by Wildman *et al*. (1982).

Grazing behaviour

Visual observation of the 13 animals in each treatment was carried out from sunrise (6:30 h) to sunset (19:20 h) at intervals of 10 min, from Day 5 to Day 8. The following activities were recorded: grazing, walking, standing, standing ruminating, lying, lying ruminating, milking, faecal sampling and silage feeding. The activity observed was regarded as being effective over a 10-min period. Observations of behaviour were made by two observers simultaneously, each located so as to view one of the herds.

Sward Measurements

Herbage mass

Herbage mass (>5 cm above ground level) was measured daily from Day 3 to Day 8. Pre-grazing herbage mass (HM) measurements were made on the day prior to grazing, while post-grazing measurements were made immediately after the cows left the paddock. Herbage samples were collected with scissors from 12 randomly allocated quadrats of 50 cm × 50 cm. A pooled sample was made from mown herbage every fourth quadrats (1 m^2). Each of the resultant three pooled samples (12 quadrats ÷ 4) was fresh weighed, sub-sampled (0.2 kg) and dried at 60°C in a forced air oven until constant weight to determine DM content.

Botanical composition

The botanical composition of the herbage was determined once during the experimental period for each treatment. Twenty five samples of herbage of approximately 0.25 kg were collected randomly to a cutting height of 5 cm above ground level with scissors before grazing. Fresh herbage was immediately separated into its botanical constituents (*i.e.*, lucerne, clovers, weed and grasses and dead matter). Each constituent was dried in a forced air oven at 60°C until constant weight to determine the botanical composition on a DM basis.

Chemical composition of feeds

Twenty-five herbage samples were collected by a hand-plucking technique (Langlands, 1974) in the morning (8:30 h) from Day 4 to Day 8, following close observation of cows to simulate grazing in each treatment. Samples of concentrate and silage were collected daily from Day 4 to Day 7. Sub-samples of 0.2 kg of lucerne pasture, silage and concentrates were weighed and dried at 60ºC in a forced air oven until constant weight to determine DM content. Dry samples were ground using a Wiley mill (Arthur H. Thomas, Philadelphia, PA, USA) to pass through a 1 mm screen and analyzed for CP (AOAC, 1990; # 976.05), neutral detergent fibre (aNDF; Van Soest *et al*., 1991), acid detergent fibre (AOAC, 1990; # 973.18), sulphuric acid lignin (lignin(sa)) according to Robertson & Van Soest (1981), ether extract (AOAC, 1990; # 920.39), ash (AOAC, 1990; # 924.05) and *in vitro* DM digestibility (IVDMD; Tilley and Terry, 1963). Heat-stable amylase and sodium sulfite were used for aNDF determination and aNDF and ADF are expressed inclusive of residual ash. Chemical composition and DM digestibility of feeds are shown in Table 1.

Table 1 Chemical composition and DM digestibility of the concentrates, silage and hand-plucked samples of lucerne pasture (mean ± SD).

	Concentrate	Sorghum silage	Pasture (High HA)	Pasture (Low HA)
DM (g/kg)	906 ± 9.2	363 ± 263	217 ± 7.2	228 ± 3.8
DM composition (g/kg)				
CP	154 ± 5.7	95 ± 3.8	242 ± 9.5	233 ± 10.7
aNDF	241 ± 4.1	576 ± 4.8	432 ± 19.3	441 ± 13.7
ADF	95 ± 3.9	316 ± 0.7	182 ± 10.7	199 ± 9.6
Lignin(sa)	27 ± 4.9	65 ± 2.7	52 ± 8.2	52 ± 3.9
Ether extract	58 ± 3.0	38 ± 2.9	28 ± 5.4	29 ± 2.2
Ash	73 ± 2.8	133 ± 1.5	119 ± 11.1	121 ± 10.6
IVDMD (g/g)	0.84 ± 0.068	0.51 ± 0.0285	0.82 ± 0.0293	0.80 ± 0.0216

CP: crude protein; aNDF: neutral detergent fibre; ADF: acid detergent fibre; lignin(sa):sulphuric acid lignin; IVDMD: *in vitro* dry matter digestibility.

Calculations

Herbage DM intake (HDMIc) based on sward cutting method

HDMIc (kg DM/cow/day) = (Pre-grazing HM – post-grazing HM) (daily grazing area / no. Cows)

Herbage growth between pre- and post-grazing samples was not accounted for because samples were within a 24 h period.

Herbage allowance and efficiency of grazing

Based on herbage mass (HM) determinations, the following parameters were calculated:

Herbage allowance (HA)
HA (kg DM/cow/day) = Pre-grazing HM × daily grazing area / no. cows

Efficiency of grazing (EG; Hodgson, 1979)
EG (at a single grazing, g/kg) = (HDMI/cow / Herbage allowance/cow × 1000)

Live weight changes

A regression polynomial of third order was fitted to actual LW measurements for each cow during lactation (15 measurements) as follows:

$$y_t = b_0 + b_1 t + b_2 t^2 + b_3 t^3$$

where y_t represents LW at day t of lactation, while b_0, b_1, b_2 and b_3 are the regression coefficients of the polynomial equation. These parameters were estimated for each cow using the REG procedure of SAS (2003). Predicted LW for each day of lactation, for each cow, were then obtained from the polynomial equation. Daily LW changes during the experimental period were calculated as the difference between the predicted values from the polynomial equation across two consecutive days.

Total faecal output

Concentrations of LIPE® reach equilibrium in faeces approximately 48 hours after initial dosage. Therefore, from Day 3, *i.e.*, 72 hours after initial dosage, faecal concentrations of LIPE® were assumed constant and faecal output calculations were made by applying the following equation:

$$Total\ faecal\ output\ (g\ DM/day) = \frac{Dosed\ intake\ marker\ (g/day)}{Marker\ concentration\ in\ faeces\ (g/g\ DM)}$$

The recovery of a marker, which is the quantity of the marker obtained from the total collection of faeces expressed as a proportion of that consumed, is an important indication of its efficacy. The estimated total faecal output should be multiplied by the rate of recovery of the marker.

In experiments using LIPE®, faecal recovery rates were 99.3 g/100g for rabbits, 102.6 g/100g for pigs, 95.9 g/100g for sheep (Saliba *et al.*, 2003; Saliba *et al.*, 2006; Rodriguez *et al.*, 2007), and 104.7 g/100g for beef cattle (Saliba *et al.*, 2006). These recovery rates did not differ from 100 g/100g (P>0.05). Therefore, a 100 g/100g recovery rate was assumed for LIPE® in the calculation of total faecal outputs in the present study.

Herbage DM intake calculated from faecal output and feed digestibility

Individual HDMI was determined from the total faecal output estimated for each cow and the group IVDMD value for consumed herbage. To obtain the faecal output from herbage (FOH), the faecal production associated with concentrate and silage was discounted from the total faecal output estimated with LIPE® and the remaining faecal material was attributed to the herbage intake (Hamilton *et al.*, 1992). The relative contributions of concentrates and silage to the total faecal output were estimated from the estimated intake of each feed for each cow and the IVDMD of each feed. The faecal output from herbage (FOH) was then calculated as follows:

$$FOH = TFO - (C.DMI \times (1 - C.IVDMD) + S.DMI \times (1 - S.IVDMD))$$

where TFO is the total faecal output estimated with LIPE®, C.DMI is the concentrate DM intake and C.IVDMD is the IVDMD of the concentrate, S.DMI is the silage DM intake and S.IVDMD is the IVDMD of the silage. Finally, herbage DM intake was calculated as follows:

Herbage DM intake (HDMIi) based on intake marker method

$$HDMIi\ (kg\ DM/cow/day) = FOH/(1 - H.IVDMD)$$

where H.IVDMD is the IVDMD of herbage.

Herbage DM intake calculated from the animal performance method

Herbage DM intake per cow was also calculated with the animal performance method (HDMIa), as the sum of metabolisable energy (ME) requirements for milk production, maintenance, pregnancy and LW change according to Freer *et al.* (2007), minus ME consumed as supplements (*i.e.*, silage and concentrates), divided by the estimated ME concentration of herbage. The LW changes for each cow were calculated as explained above.

Statistical analyses

All data were analysed using SAS (2003). All animal variables were analysed considering cow as the experimental unit. Milk yield, milk fat content, milk crude protein content, HDMI estimated with LIPE®, total DM intake and grazing behaviour variables were averaged per cow for the experimental period (Day 4 to Day 8) and analysed using the MIXED procedure. The linear model included the fixed effects of HA and parity, and proportion of Jersey genes and days in milk as covariables, and the random effect of cow nested within treatment. Mean differences between treatment effects were declared significant at a probability <0.05.

Pre-grazing herbage mass, HA and HDMI calculated from the herbage mass method were evaluated using the MIXED procedure. The linear model included the fixed effects of HA and the random effect of day of sampling and the interaction of HA x day of sampling, which was used to derive the F value for testing the significance of the interaction term.

The accuracy of prediction of HDMI using LIPE® was tested against the estimates of HDMI calculated from ME requirements (animal performance method) using the mean square prediction error (MSPE) defined by Fuentes-Pila *et al.* (1996) as:

$$MSPE = \frac{1}{n}\sum_{i=1}^{n}(A_i - P_i)^2$$

where A is the HDMI calculated from ME requirements (animal performance method), P is the HDMI estimated using LIPE® and n is the number of pairs of values of A and P being compared. The fitness of the model was evaluated by the relative prediction error (RPE) defined as the ratio between the positive root square of the MSPE and the mean of the actual intake values (A). Fuentes-Pila *et al.* (1996) suggested that a RPE value lower than 10% is an indication of satisfactory prediction, between 10% and 20 % indicates relatively good or acceptable predictions, and greater than 20% indicates poor predictions.

The concordance correlation coefficient (CCC) was also calculated to test the agreement between methods (Lin, 1989). It is calculated as: CCC = $\rho \times C_b$, with ρ the Pearson correlation coefficient and C_b a bias correction factor. The Pearson correlation coefficient reflects precision, *i.e.*, degree to which the predicted against actual values cluster about the regression line. The bias correction factor reflects accuracy, *i.e.*, degree to which the regression line adheres to the 45° line through the origin. The scale of Landis and Koch (1977) has been used here to describe the degree of concordance, with: 0.21–0.40 being “Fair”; 0.41–0.60 being “Moderate”; 0.61–0.80 being “Substantial”; and 0.81–1.00 being “Almost perfect”.

RESULTS

Weather

From Day 4 to Day 8, when all measurements were taken, mean air temperature was 17.7 ± 2.54°C, minimum air temperature was 9.2 ± 3.34°C and maximum air temperature was 26.3 ± 2.12°C and no rainfall was recorded.

Herbage quality and botanical composition

The chemical composition and the IVDMD of herbage are shown in Table 1. Overall, herbage quality was similar in both treatments.

The botanical composition for the high HA paddocks was: lucerne 0.92 ± 0.074, clovers 0.04 ± 0.048, weeds and grasses 0.02 ± 045 and dead matter 0.02 ± 0.017 and for the low HA paddocks: lucerne 0.91 ± 0.103, clovers 0.03 ± 0.039, weeds and grasses 0.03 ± 0.077 and dead matter 0.03 ± 0.017.

Feeds intake

Pre-grazing herbage mass was similar for both HA treatments (Table 2). Herbage DM intake was higher for low than high HA ($P<0.05$) as estimated by the LIPE® method and the animal performance method, but no differences were detected between treatments when intake was calculated from pre- and post-grazing herbage mass measurements (Table 2).

Cows at the lower HA had higher silage DM intake ($P<0.05$), which partially compensated for their lower HDMI, and therefore, total DM intake was similar for both treatments (Table 2).

Table 2 Pre-grazing herbage mass, herbage allowance (HA), herbage DM intake estimated with LIPE®, animal performance and sward cutting methods, metabolisable energy intake, efficiency of grazing and supplements intake at the high and low herbage allowance treatments.

	Herbage allowance (Kg DM/cow/day)		SEM
	14.5	10.0	
Pre-grazing herbage mass (kg DM/ha)	1743	1608	105.6
Herbage allowance (HA, kg DM/cow/d)	14.3_a	10.2_b	0.73
Herbage intake[1]			
Sward cutting method, kg DM/cow/d	9.6	8.9	0.74
Animal performance method, kg DM/cow/d	11.0_a	9.7_b	0.42
LIPE® method, kg DM/cow/d	10.8_a	9.7_b	0.37
Efficiency of grazing[2] (%)	66.6_a	87.2_b	3.37
Silage consumed (kg DM)	3.1_a	3.4_b	0.08
Concentrates consumed (kg DM)	5.6	5.6	-
Total intake (kg DM)	19.5	18.7	0.33
Total ME intake (MJ ME/cow/d)	227_a	215_b	4.2

[a and b] For the same row, means with different subscripts differ ($P<0.05$).
[1]Herbage DM intake (HDMI).
[2]Calculated using the sward cutting method (herbage DM intake/herbage allowance × 1000; g/kg DM) (Hodgson, 1979).

Milk production, milk composition, feed conversion efficiency and live weight

Milk yield was higher (P<0.05) for cows at the high HA than for cows at the low HA, but percentages of milk fat and milk crude protein did not differ between treatments (Table 3). This resulted in increased milk crude protein yield by (+0.13 kg/cow/day) and milk fat yield (+0.15 kg/cow/day) per cow for high HA compared to low HA (P<0.01). The FCEs were 123 and 114 g MS/kg DM consumed for high HA and low HA, respectively (P>0.05). Total ME intake was higher (P<0.05) for high HA cows (Table 3). Neither LW at calving nor LW change during experimental days differed between treatments (Table 3).

Table 3 Milk yield cow, milk composition, feed conversion efficiency and live weight (LW) change at the high and low herbage allowance treatments.

	Herbage allowance (Kg DM/cow/day)		SEM
	14.5	10.0	
Days in milk	83	85	1.8
Milk yield (kg/cow/day)	33.2_a	29.1_b	1.84
Fat yield (kg/cow/day)	1.26_a	1.11_b	0.034
Crude protein yield (kg/cow/day)	1.13_a	1.00_b	0.032
Milk composition (%)			
Fat	3.86	3.83	0.154
Crude protein	3.43	3.46	0.639
Feed conversion efficiency[1]	123	114	3.9
LW at day 1 of lactation (kg/cow)	468	458	16.6
LW change during experiment (kg/cow/day)	-0.22	-0.04	0.147

[a and b] For the same row, means with different subscripts differ (P<0.05).
[1]Feed conversion efficiency (FCE, Kolver, 2007) = g milksolids per kg DM intake (estimated with the LIPE® method).

Visual observation of grazing behaviour

Daily times at pasture were 9.1 hours for high HA and 8.6 hours for low HA cows and therefore, the recorded grazing times of 4.3 h and 4.7 h represented 47% and 55% of daily time at pasture for high and low HA, respectively (Table 4).

Cows at the high HA spent less time grazing (P<0.05) and walking (P<0.01), more time lying (P<0.01) and less time eating silage than cows at the low HA (Table 4). The time spent standing and ruminating did not differ between treatments (Table 4).

Table 4 Means of time (minutes/ d) spent at grazing, standing, lying, ruminating, walking, eating silage and at other activities for cows at the two herbage allowances, based on visual observations during 12.9 h of daylight.

Time (minutes/day)	Herbage allowance (Kg DM/cow/day)		SEM
	14.5	10.0	
Grazing	258_a	284_b	7.2
Standing and ruminating	16	20	3.4
Lying and ruminating	23	14	3.5
Standing [1]	109	91	7.9
Lying[2]	112_a	58_b	7.7
Walking[3]	23_a	40_b	1.7
Eating silage[4]	125	157	-
Other[4,5]	103	105	-

[a and b] For the same row, means with different subscripts differ (P<0.05).
[1] Cows drinking were record as standing.
[2] Cows grazing while lying were recorded as lying.
[3] Cows ruminating at the same time as walking were recorded as walking.
[4] All the cows in each treatment spent the same time in this activity (no individual measurements available).
[5] Other: Milking and faecal extraction.

Comparison of LIPE® versus animal performance estimates of herbage DM intake

Figure 1 show the relationship between HDMI estimated with the LIPE® method and HDMI estimated with the animal performance method, using the average of 5 days per cow in both cases. The relationship between the animal performance method and the LIPE® method was significant (P<0.01), with a correlation coefficient of 0.65, a CCC of 0.57 and a RPE of 16%.

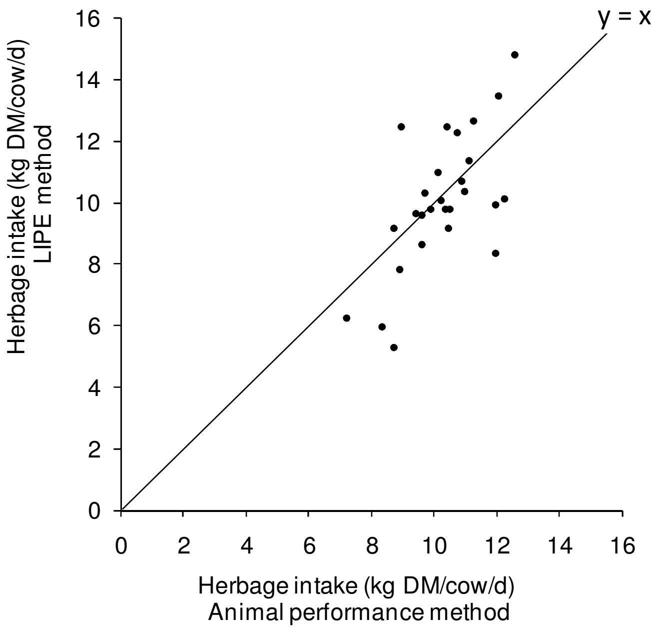

Figure 1 Relationship between herbage DM intake (HDMI) estimated from the LIPE® method and the animal performance method. One data point plotted per cow, averaged over the 5-day period. The relationship was significant (P<0.01), with a correlation coefficient of 0.65, a CCC of 0.57 and a relative prediction error of 16%.

DISCUSSION

The aims of this study were to evaluate the effects of HA on individual HDMI, milk yield and grazing behaviour of supplemented dairy cows grazing lucerne-based pastures in early lactation, and to compare two methods to estimate individual HDMI: the animal performance method and the LIPE® method.

Feed intake and efficiency of grazing

The HDMI was higher for cows in the high HA treatment than for cows in the low HA treatment when the LIPE® method and the animal performance method were used, however, no differences between treatments were detected with the sward cutting method. This highlights the importance of using dietary markers to investigate the effect of HA on HDMI for cows grazing lucerne-based pastures, because the intake marker provides information of HDMI for each cow, giving more statistical power to detect differences than methods that measure HDMI for a group of cows. However, this does not mean that intake marker is more accurate than other methods to estimated HDMI.

The efficiency of grazing (HDMI ÷ HA × 1000) was 210 g/kg higher ($P<0.05$) for cows at low HA than for cows at high HA. This indicates that cows grazing lucerne pastures can partially compensate for the lower HA by increasing the efficiency of grazing, as suggested by Romero *et al.* (1995). However, this compensation is only possible within a range of HA. These results also suggest that high efficiency of grazing of 870 g/kg can be obtained at low HA, even when cows were offered moderate to high amounts of supplements, which can be the case in dairy systems with high stocking rate and moderate to high levels of supplementation.

Comparison of LIPE® versus animal performance estimates of herbage DM intake

Macoon *et al.* (2003) compared HDMI estimates from the animal performance method with estimates from an intake marker method and the sward cutting method for dairy cows grazing at two SRs. In their study, differences between SR treatments were detected with the animal performance and sward cutting methods, but not with the intake marker method. When using the sward cutting method, they measured HDMI for each cow, in contrast with the present experiment, which measured HDMI for a group of cows (n=13).

The intake marker used by Macoon *et al.* (2003) was a pulse-dose marker (chromium-mordanted fiber). They reported a positive correlation between the animal performance method and the sward cutting method, but no significant correlation between the animal performance method and the pulse-dose marker and between the pulse-marker and the sward cutting method (Table 5). These authors attributed the lack of empirical relationships between the marker and the other two methods to possible dosing errors, the frequent disturbance of animals, numerous laboratory analyses, and the complexity of modelling marker flow and calculating the parameters.

Smit *et al.* (2005) compared estimates of HDMI from the animal performance method with an intake marker method (n-alkane) and with the sward cutting method (using individual animals) for grazing dairy cows. In their study, positive and significant correlations were found between all three methods (Table 5).

In the current study, there was a positive correlation (R= 0.65, P<0.01) between the animal performance method and the intake marker (LIPE®) method. The accuracy of the prediction of LIPE® against the animal performance method is considered relatively good (Fuentes-Pila *et al.*, 1996), with a RPE between 10% and 20% and it is considered moderate (Landis and Koch, 1977), with a CCC of 0.57.

Table 5 Correlation coefficients of the relationships between the sward cutting method, the intake marker methods and the animal performance method in three studies.

Reference		Sward cutting	Animal performance
Macoon *et al.,* 2003	Intake marker[1]	0.09	0.06
	Animal performance	0.57***	
Smit *et al.*, 2005	Intake marker[2]	0.40**	0.50***
	Sward cutting		0.43**
Present study	Intake marker[3]		0.65**

*P<0.05; **P<0.01; ***P<0.001.
[1]Pulse-dosed marker (chromium-mordant fiber).
[2]n-alkane.
[3]LIPE®.

Dosing of LIPE® could be considered a possible cause for overestimation of intake. As explained in the methodology section, animals were observed individually after oral dosing, to make sure that capsules were not rejected. On three occasions LIPE® capsule regurgitation was observed, and the same capsule was re-administered. However, after the animals left the yard, some capsules could have been regurgitated. If this occurred, it would have resulted in falsely low faecal marker concentration in faeces, and thus overestimation of faecal output leading to overestimation of intake.

One limitation of the animal performance method is the difficulty of accurately measuring changes in LW of animals with time, especially over such short periods (Macoon *et al.*, 2003). Because cows used in this experiment were weighed frequently during the whole lactation, the methodology used to estimate LW change (prediction of daily LW with third order polynomials) in our study can be considered more accurate than estimations of LW change based on the difference in LW recorded during the experimental period.

Milk production, milk composition and feed conversion efficiency

Cows at the higher HA produced 4.1 kg milk more per cow/day than cows at the lower HA (Table 3). Estimates of ME consumed (Freer *et al.*, 2007) indicate that cows at the higher HA consumed 12 MJ ME per cow/day more than cows at the lower HA (Table 3). The rest of the extra energy required to produce the extra milk (4.1 kg milk x 5.1 MJ ME per kg milk = 20.9 MJ ME/cow/day) at lower HA must have been provided from body lipid mobilisation. It could also be explained by experimental errors in estimations of intake, feeds quality and LW change.

Milk fat and milk crude protein percentages were not affected by HA, in agreement with previous short-term studies of cows grazing ryegrass-based pastures at different allowances in early lactation (Kennedy *et al.*, 2008), or in mid-late lactation (Robaina *et al.*, 1998), cows grazing a mix of grasses in mid lactation (Bargo *et al.*, 2002) and cows grazing lucerne-based pastures in mid lactation (Alvarez *et al.,* 2006).

In the current study, there was no effect of HA on FCE (Table 4). This agrees with Tozer *et al.* (2004), who compared the performance of dairy cows offered HA of 25 and 40 kg DM/cow/day (to ground level) and found no differences in FCE.

Laborde *et al.* (1998), using New Zealand Holstein Friesian dairy cows (85 to 91 days in milk) reported FCE of 143 to 144 g MS per kg DM consumed (milksolid yields ranged from 1.5 to 1.7kg/cow/day), while Bargo *et al.* (2002), reported FCE of 67 to 74 g MS per kg DM consumed for North American Holstein Friesian cows with 101 days in milk (milksolids yield ranged from 1.3 to 2.0 kg/cow/day). The values for FCE obtained in the present study (114 to123 g MS per kg DM consumed) are between those of the two other studies reported here. Differences in FCE in these three studies may be explained by differences in milk volume, milk fat and milk crude protein concentrations, with the study of Bargo *et* *al.* (2002) having the highest milk volume and the lowest crude protein and fat concentrations, and the study of Laborde *et al.* (1998) having the lowest milk volume and highest crude protein and fat concentrations.

Grazing behaviour

Grazing conditions such as HA or sward height, which partly determine herbage availability and herbage intake rate, can affect the time spent grazing (Chilibroste *et al.*, 2007; Perez-Ramirez *et al.*, 2009). Sheep and cattle increase grazing time as HA declines, in an effort to meet their intake requirements (Allden & Whittaker, 1970).

Grazing time increased at the higher of two SRs for steers grazing lucerne pastures (Popp *et al.*, 1997) and steers grazing tall fescue (Seman *et al.*, 1991). In agreement with these studies, grazing time increased by 26 minutes/day as HA decreased from 14.3 to 10.3 kg DM/cow/day in the present study. In our study, cows at high HA spent less time eating silage, which is in agreement with their lower silage DM intake (Table 2).

Stockdale and King (1983) reported that virtually no grazing occurred between 21:00 h and milking time the next morning, and that rumination and resting mainly occurred at night for dairy cows. This possibly explains the short time that cows spent ruminating during the day time in our current study. A further explanation for the short time that cows were observed ruminating is that ruminating time was not recorded while cows were eating silage, at milking or at faecal sampling in the present study. Even though our study reports only daylight grazing behaviour in the paddock, this is the first study reporting grazing behaviour of dairy cows grazing on lucerne-based pastures.

CONCLUSIONS

Herbage DM intake differed between treatments ($P<0.05$) when using both the LIPE® method and the animal performance method, which are based on estimates of individual intakes. However, when using the sward cutting method, based on herd average intake, HDMI did not differ between treatments ($P>0.05$).This highlights the importance of using dietary markers to investigate the relationship between HA and HDMI for cows grazing lucerne-based pastures.

Cows at the high HA treatment had greater HDMI and milk yield, but had an efficiency of grazing 210 g/kg lower than cows at the low HA. This study showed that lucerne pasture can be utilised at grazing with high efficiency (870 g/kg) at low HA, even with cows offered moderate to high amounts of supplements.

Estimates of HDMI measured with LIPE® were close to animal performance estimates. However, further research is needed to explore the suitability of LIPE® to predict HDMI for dairy cows at grazing. More research is also required to investigate the relationship between HA and individual HDMI, exploring a wider range of herbage allowances for dairy cows grazing lucerne-based pastures.

ACKNOWLEDGEMENTS

The authors thank Instituto Nacional de Tecnologia Agropecuaria, Massey University and Facultad de Ciencias Agrarias–UNL for their funding to this study.

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Chapter 5

Prediction of herbage dry matter intake for dairy cows grazing ryegrass-based pastures

J. Baudracco[1], N. Lopez-Villalobos[1], C.W. Holmes[1] and K.A. Macdonald[2]

[1]Institute of Veterinary, Animal and Biomedical Sciences, Massey University, Private Bag 11-222, Palmerston North, New Zealand

[2]DairyNZ , Private Bag 3221, Hamilton, New Zealand

Published 2010 in Proc. New Zealand Society of Animal Production 70: 80-85

ABSTRACT

A model that combines theoretical and empirical equations was developed to predict daily dry matter intake (DMI) for Holstein-Friesian (HF) cows grazing ryegrass-based swards and offered differing levels of concentrate supplementation. An upper limit to potential herbage dry matter (DM) intake at grazing is set, which is the lower of three limits set by either physical (rumen fill), metabolic (energy demand) or grazing restrictions. Potential herbage DMI at grazing and the herbage allowance are then used to predict herbage DMI, of cows fed only pasture, using an empirical algorithm. If supplements are fed, substitution rate is predicted to calculate actual herbage DMI. An independent dataset, with individual herbage DMI measurements (n=1,147) of three strains of lactating HF cows, was used to validate the model. Data within strains were averaged for every month of lactation, allowing 27 data points for validation. The fitness of the model was satisfactory, with a relative prediction error of 8.3% and a concordance correlation coefficient of 0.74. Herbage DMI was simulated for HF cows of different genotypes fed different levels of concentrate supplementation at different herbage allowances. The model successfully predicts herbage DMI of grazing cows under different combinations of nutritional, physiological and genetic variables.

INTRODUCTION

Livestock production is highly correlated with dry matter intake (DMI). In grassland grazing systems, low and variable herbage intake has been reported as a strong constraint of milk production in high genetic merit dairy cows (Boudon *et al.*, 2009). Accurate prediction of herbage dry matter (DM) intake can improve herbage allocation and herbage intake in grazing dairy systems (Woodward *et al.*, 2001).

Different approaches have been used to predict herbage intake of grazing cattle. Among them, mechanistic and empirical models have been developed, focusing on ingestive behaviour (Woodward *et al.*, 2008), rumen digestion (Chilibroste *et al.*, 1997) sward characteristics and grazing management (Heard *et al.*, 2004; Delagarde *et al.* 2011), animal characteristics (Caird & Holmes, 1986) or animal physiological state (Gregorini *et al.,* 2009).

The set of inputs required by a model to predict herbage DMI could be complex, because of the characteristics of swards and animals, and of the biological processes involved in food selection, ingestion and digestion. Researchers are challenged by the need to develop models that account for an increased amount of information while maintaining simplicity. An easy-to-obtain set of inputs will increase the practical usefulness of the model (Gregorini *et al.*, 2009). The model proposed in this study combines theoretical and empirical equations to predict herbage DMI, requires an easy-to-obtain set of inputs and is sensitive to nutritional, physiological and genetic factors of the cows.

The objectives of this study were to develop a model to predict daily DMI of ryegrass (*Lolium perenne* L.) pastures for grazing Holstein Friesian (HF) cows, and to simulate herbage DMI of two different genotypes of HF cows under different levels of concentrate supplementation and herbage allowance.

MATERIALS AND METHODS

Model overview

A model initially developed to predict herbage DMI of cows grazing lucerne (*Medicago sativa* L.) pastures (Baudracco *et al.*, 2006), was adapted to predict daily herbage DMI of lactating HF dairy cows grazing ryegrass-based pastures. The model sets an upper limit to potential herbage DMI at grazing (*PotDMI*) for cows fed only pasture, which is the minimum out of three limits:

i) Physical limitation to rumen fill ($PotDMI_r$),

ii) Metabolic limitation to energy demand ($PotDMI_e$) and

iii) A 'grazing limit' of 37.5 g herbage DMI per kg LW ($PotDMI_g$).

The minimum *PotDMI* and the herbage allowance (kg DM/cow/day) are used to predict herbage DMI of cows fed only pasture ($HerbDMI_o$) by using an empirical algorithm. When supplements are used, an algorithm that predicts substitution rate is used to predict actual herbage DMI. The model requires the following inputs: live weight (LW), days in milk, days pregnant, potential milk yield, herbage allowance, pasture neutral detergent fibre (NDF) content, pasture ME content and kg DM supplements consumed.

Potential herbage DM intake at grazing

Potential herbage DMI at grazing (*PotDMI*) expresses the maximum intake possible for cows fed only pasture. It is calculated as the minimum of metabolic ($PotDMI_e$), physical ($PotDMI_r$) and grazing ($PotDMI_g$) limits.

Metabolic limit to intake

The metabolic limit to intake ($PotDMI_e$) is calculated as total metabolisable energy (ME) requirements (*MEReq*) divided by ME concentration of pasture (*PastME*), as shown in the following equations:

$$PotDMI_e\ (kg\ DM/cow/day) = MEReq\ /\ PastME \quad (1)$$

$$MEReq\ (MJ\ ME/cow/day) = ME_m + ME_p + (ME_l\ Y) \quad (2)$$

where ME_m and ME_p are the ME required for maintenance and pregnancy, respectively. ME_l is the ME required to synthesize one litre of milk, and Y is the potential milk yield per cow (litres/day). Requirements for ME_m, ME_p and ME_l are calculated according to Freer *et al.* (2007).

Potential milk yield is calculated on the basis of a mathematical mammary gland model (Vetharaniam *et al.*, 2003) based on the interaction of two pools of alveoli (groups of secretory cells), one active pool and one quiescent pool. The equation to predict milk production, *Y*, proposed in this mammary gland model is:

$$Y\ (kg/day) = SE^L \frac{(de^{-k2\ t} + l6\ e^{w6\ t} + l7\ e^{w7\ t})}{kl\ x\ MEl} \quad (3)$$

where *S* is the maximum milk secretion rate of active alveoli, *t* is the time after parturition (days), *E* is the energy status at day *t*, *L* is a parameter that governs the response of milk yield to nutrition, and *d*, k_2, *l*6, *w*6, *l*7, *w*7, are parameters related to the alveolar dynamics, *i.e.*, number of active, quiescent and senescent alveoli. Detailed explanation about the latter parameters can be found in Vetharaniam *et al.* (2003). The *MEl* was defined in Equation 2 and *Kl* is a coefficient accounting for the efficiency of utilisation of ME for milk synthesis. The energy status, *E*, was set to 1 because *Y* represents potential milk yield (no nutritional limitations) in the present model.

Potential milk yield is estimated using the parameters reported by Vetharaniam *et al*. (2003) for first lactation cows of both New Zealand HF and North American HF strains fed TMR diets (no nutritional limitations). The constant S was re-parameterised for herds with 79% multiparous cows and lactation yields of either 10,097 and 7,304 kg milk per cow for North American and New Zealand strains (Kolver *et al*., 2002), respectively.

Physical limit to intake

The physical limitation model developed by Mertens (1987) states that, when the fill effect of the diet is high, daily potential intake ($PotDMI_r$) can be expressed as a constant rumen capacity (*C*) divided by the fill effect (*F*) of the diet:

$$PotDMI_r(kg\ DM/day) = \frac{C}{F} \quad (4)$$

In the current model, it was assumed that the animal has a potential neutral detergent fibre (NDF) rumen capacity, and that the feeds have a given capacity to occupy space determined by its NDF content. Given that ruminal volume is a function of body weight, rumen capacity is expressed in the model in terms of kg of NDF as percentage of the body weight. Therefore, Equation 4 can be re-arranged as follows:

$$PotDMI_r = \frac{0.0165\ LW}{Pasture\ NDF}\ SOL \quad (5)$$

The term 0.0165 times LW is supported by data from Vazquez & Smith (2000), which show that, at high herbage allowance (HA), the average daily intake of NDF was

1.65% of LW. The SOL is a coefficient accounting for the effect of stage of lactation on rumen capacity, which is defined in Equation 6, as proposed by Hulme *et al.* (1986):

$$SOL = 0.67 + (4.0401\ \mathrm{Log}(w) - 0.095\, w + 0.095)\ 0.0972 \quad (6)$$

where w is the week of lactation.

Grazing limit to intake

A 'grazing limit' ($PotDMI_g$) was defined as follows:

$$PotDMI_g = \mathrm{LW} \times 0.0375 \times \mathrm{SOL} \quad (7)$$

This value of 3.75% of LW is based on maximum intakes measured for high yielding HF cows grazing with no pasture quality or quantity restrictions (Kolver & Muller, 1998; Mayne & Wright, 1988). The $PotDMI_g$ sets an upper limit to maximum herbage DMI in cases of high yielding cows consuming pastures with low NDF, in which case the physical ($PotDMI_r$) and metabolic ($PotDMI_e$) limits set unrealistically high values to herbage DMI at grazing.

Herbage DM intake of cows fed only pasture (HerbDMI$_0$)

The minimum between $PotDMI_r$, $PotDMI_e$ and $PotDMI_g$ is selected as the final potential herbage DMI at grazing (*PotDMI*). The extent to which the cow achieves her *PotDMI* depends on HA. The ratio of HA to *PotDMI* (*HA*/*PotDMI*) is a measure of the pasture offered relative to the cow's demand for pasture at grazing, and it is used to predict actual herbage DMI in the present model. For instance, assuming a HA of 40 kg DM/cow/day and a *PotDMI* of 20 kg DM/cow/day, the ratio of HA to *PotDMI* will be 2.

This theoretical framework was used to calculate the *PotDMI* and the ratio *HA*/*PotDMI* for un-supplemented treatments of 9 experiments with cows grazing ryegrass-based pastures, and in which HA was measured to ground level. In Figure 1, the calculated ratio *HA*/*PotDMI* and the measured harvesting efficiency of those experiments are regressed, and the empirical equation obtained from Figure 1 is used to predict harvesting efficiency and actual herbage DMI of cows fed only pasture.

Harvesting efficiency is used as a synonym of efficiency of grazing here. Using the example given (*HA*/*PotDMI* = 2), harvesting efficiency (*HE*; herbage consumed:HA x 100) and pasture DMI ($HerbDMI_0$) can be predicted using the Equation derived from Figure 1, as follows:

$$HE\ (\%) = 57.676\left(\frac{HA}{PotDMI}\right)^{-0.536} = 39.8 \quad (8)$$

$$HerbDMIo\ (kg\ DM/day) = HA\ (HE) = 40\ (39.78\ \frac{1}{100}) = 15.9 \quad (9)$$

Thus, the *PotDMI* is both a limit and a driver for herbage DM intake (Figure 1).

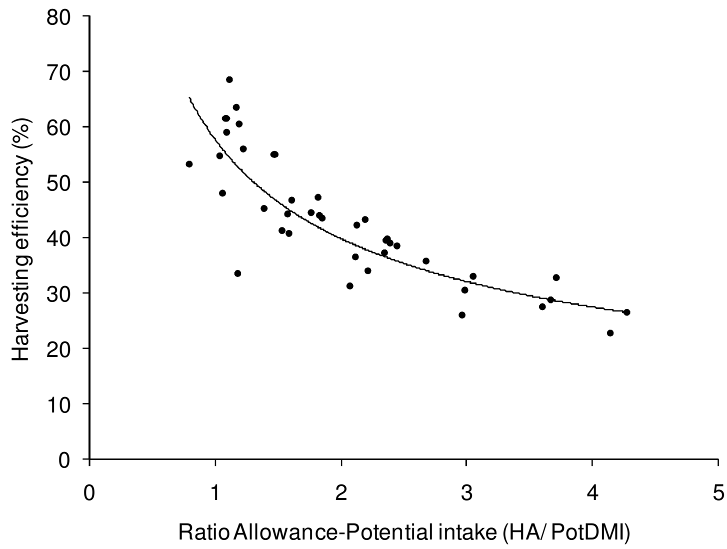

Figure 1 Harvesting efficiency (HE, herbage consumed: herbage allowance x 100) as a function of the ratio herbage allowance: *PotDMI* (HA/ *PotDMI*), using data from un-supplemented treatments of 9 short-term grazing experiments with ryegrass-based pastures (Robaina *et al.*, 1998; Wales *et al.*, 1998; Dalley *et al.*, 1999; Stockdale, 1999; Wales *et al.*, 1999; Dalley *et al.*, 2001; Wales *et al.*, 2001; Ribeiro *et al.*, 2005; Lee *et al.*, 2008). Herbage allowance was measured to ground level in all the studies. HE = 57.676 $(HA/PotDMI)^{-0.536}$ (R^2 =0.749).

Herbage DM intake of cows fed supplements ($HerbDMI_s$)

The predicted herbage DMI of cows fed supplements (*$HerbDMI_s$*) is calculated with Equation 10:

$$HerbDMI_s = HerbDMIo - (SR)SupplDMI \qquad (10)$$

Substitution rate (SubR) expresses the decrease in kg DMI of herbage per kg DMI of supplement (SuppDMI), and it is calculated as follows:

$$\text{SubR} = 0.21\ \text{HDMI} - 0.18; (\text{Stockdale, 2000}) \qquad (11)$$

where *HDMI* is herbage DMI before supplementation, expressed as kg DM/100 kg LW. In the present model, the value for *HDMI* is calculated as:

$$HDMI = \frac{HerbDMIo}{LW} 100 \qquad (12)$$

Correction of Pasture DM intake of supplemented cows

In cases of high level of supplementation, the predicted total (supplements plus herbge) ME intake may exceed the metabolic limit to intake, set by the ME requirements (MEReq). Therefore, in those cases, recalculation of the values obtained in equations 10 and 11 is needed to obtain new values for herbage DM intake (HerbDMIs) and substitution rate (SubR), because total ME intake cannot exceed total ME requirements (MEReq). Thus, if the predicted total ME intake (ME intake from herbage plus supplements) is greater than MEReq, then the recalculated HerbDMIs and SubR are:

$$\text{HerbDMIs} = \frac{\text{MEReq} - (\text{SuppDMI x SuppME})}{\text{PastME}} \qquad (13)$$

$$\text{SubR} = \frac{\text{HerbDMIu} - \text{HerbDMI0}}{\text{SuppDMI}} \qquad (14)$$

Where SuppME is the ME content per kg DM of supplement. This correction allows the genetic merit of the cow to affect the SubR at high HA and high levels of supplementation, since cows with different potential milk yield have different MEReq.

Model validation

An independent dataset was obtained from a trial with three strains of HF cows grazing ryegrass-clover pasture in New Zealand (Macdonald *et al.*, 2008). The strains were North American HF 90s (NA90; ≥ 91% North American genetics), New Zealand HF 90s (NZ90; ≤ 24% North American genetics) and New Zealand HF 70s (NZ70; ≤ 7% North American genetics). The dataset comprised individual herbage DMI measurements (n=1,147) with the n-alkanes technique for lactating cows over two lactations. Data were grouped by strain and month of lactation, resulting in 27 data points for validation of the whole dataset and 9 points for validation within each strain. Mean values in the dataset were: 505 kg LW (range 352 to 750 kg), 43.7 kg DM/cow/day HA (range 30.2 to 69.0 kg), 37.9% pasture NDF (range 30.7 to 48.0%) and 14.6 kg DM/cow/day herbage DMI (range 7.5 to 24.0 kg). Herbage allowance was measured to ground level.

Predicted herbage DMI values (P) were compared against actual observed herbage DMI values (A) using the mean square prediction error (MSPE) defined by Fuentes-Pila *et al.* (1996) as:

$$MSPE = \frac{1}{n}\sum(A-P)^2 \qquad (15)$$

where *n* is the number of pairs of values of *A* and *P* being compared.

The fitness of the model was evaluated by the relative prediction error (RPE) defined as the ratio between the positive root square of the MSPE and the mean of the actual intake values (Fuentes-Pila *et al.*, 2003) and by the concordance correlation coefficient (CCC) (Lin, 1989). The accuracy of the prediction was considered satisfactory when the RPE was lower than 10% (Fuentes-Pila *et al.*, 1996). Additionally, the mean bias (kg/day) was calculated, which is defined as the difference between the mean of the actual intake values and the mean of the predicted intake values (Fuentes-Pila *et al.*, 2003).

RESULTS

Model validation

For the whole dataset taken from Macdonald *et al.* (2008), the MSPE was 1.40, the RPE 8.3%, the CCC 0.74 and the mean bias +0.03 kg DM. Per strain, the RPE were 8.4%, 8.7% and 6.0%, the CCC 0.67, 0.72 and 0.75, and the mean bias were -0.82, +0.95 and -0.18 kg herbage DMI/cow/day for NA90, NZ90 and NZ70 strains, respectively. Figure 2 shows the relationship between predicted and actual intake values per month of lactation for each strain.

Model simulations

Herbage DMI was simulated for both NA90 and NZ90 HF strains, for eight levels of herbage allowance and two levels of concentrate supplementation (Figure 3).

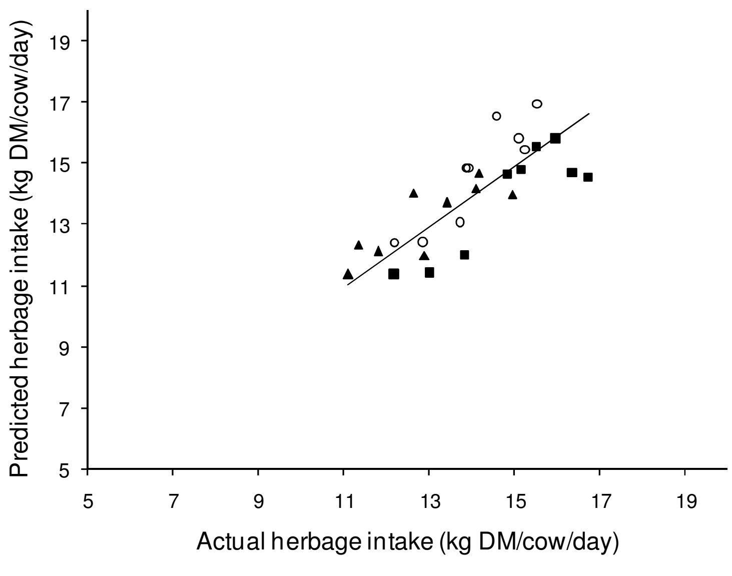

Figure 2 Actual versus predicted herbage intake (kg DM/cow/day) for the three strains of Holstein-Friesian: NA90 (○), NZ90 (■) and NZ70 (▲). One data point plotted per month of lactation for each strain. The solid line (y = x) indicates the position of the perfect fit between actual and model predicted values.

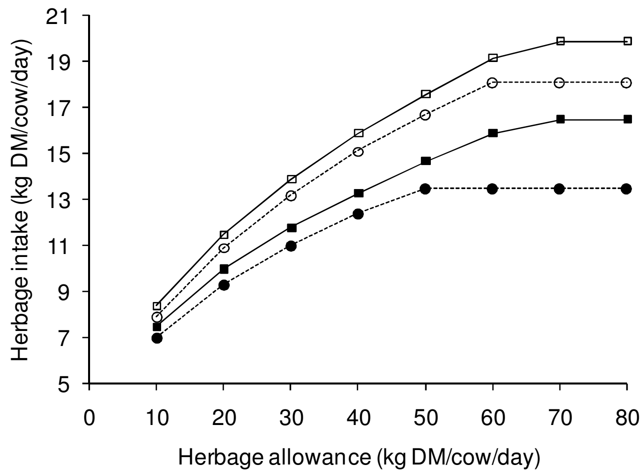

Figure 3 Simulated herbage DM intake for cows fed either pasture or pasture plus 6 kg DM/cow/day supplements. North American 90s fed solely pasture (—□—), New Zealand 90s fed solely pasture (···○···), North American 90s fed 6 kg DM supplement (—■—), New Zealand 90s fed 6 kg DM supplement (···●···). Simulations for cows of 550 kg LW (NA90) and 500 kg LW (NZ90), 80 days in milk, fed pasture with 45% NDF and daily potential milksolid yields of 2.1 kg (NZ90) and 2.5 kg (NA90).

DISCUSSION

The RPEs lower than 10%, obtained in the validation of the model, indicate that the model had satisfactory level of accuracy for both the complete dataset and data within strains, based on the study of Fuentes-Pila *et al.* (1996). Measured herbage intakes were close to predicted herbage intakes, with a mean bias (actual – predicted) of -0.82 (NA90), +0.95 (NZ90) and -0.18 (NZ70) kg herbage DMI/cow/day. These deviations from actual intake are less than or equal to those of similar studies (Delagarde & O'Donovan, 2005; Gregorini *et al.*, 2009).

Predicted intakes may deviate from actual intakes due to short-term changes in body reserves (Caird & Holmes, 1986), not accounted for in the current model. Also, deviations from model prediction suggest that there are some strain-related factors not accounted for in the model, which caused greater than predicted herbage DMI for NZ90 and lower than predicted herbage DMI for NA90. One of these unaccounted factors could be related to the 'grazing ability' of the cow. Lower ability to achieve high levels of herbage DMI at grazing (as % LW) was reported for North American HF than for New Zealand HF cows (Kolver *et al.*, 2002; Kolver *et al.*, 2005).

In a trial comparing grazing behaviour of HF strains, the NZ HF strain had a longer grazing time per day than two NA HF strains (McCarthy *et al.*, 2007) when fed on pasture only. This was unexpected based on the lower potential milk yield of the NZ HF than the NA HF strains, suggesting a greater inherent grazing drive for NZ HF. This is supported by the historical long-term selection of NZ HF cows, based on milk fat and protein production, feed conversion efficiency (g milk solids/kg DM intake) and longevity on a predominantly grass-based diet.

The typical asymptotic relationship between HA and herbage DMI for cows fed solely pasture is also observed in the current model simulations depicted in Figure 3. Thus, herbage DMI increased as HA increased up to a maximum of 18.1 (NZ90) and 19.9 kg DM/cow/day (NA90).

Predicted substitution rates also increased as HA increased, from 0.45 to 0.77 kg DM/kg DM (NZ90) and from 0.43 to 0.57 kg DM/kg DM (NA90) as HA increased from 40 to 70 kg DM/cow/day (Figure 3). The increase in substitution rate as HA increased agrees with previous studies (Robaina *et al.*, 1998; Wales *et al.*, 1999). The difference in substitution rate between HF strains agrees with results from Kolver *et al.* (2005), who found substitution rates of 0.75 and 0.67 kg DM/kg DM for New Zealand HF (< 13% NA genetics) and North American HF (>87% NA genetics) cows, respectively, when fed generously on pasture (HA range 50 to 70 kg DM/cow/day) and supplemented with 6 kg DM concentrates. The lower substitution rates predicted for NA HF cows occurred because the model set a greater metabolic limit to intake for NA HF than NZ HF cows ($PotDMI_e$), given the higher potential milk yield of the former.

The current model predicted herbage DMI with acceptable accuracy for cows of HF strains and can simulate different feeding scenarios by changing herbage allowance and the level of supplementation. The model could be improved by accounting for the different abilities of grazing of different HF strains, for example by using different values for maximum intake as percentage of LW in potential DMI calculations ($PotDIM_g$). The present model combines a simple approach to predict herbage DMI, using a set of inputs that are relatively easy–to-obtain, while accounting for nutritional, physiological and genetic variables.

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Chapter 6

e-Cow: an animal model that predicts herbage intake, milk yield and live weight change in dairy cows grazing temperate pastures, with and without supplementary feeding

J. Baudracco[1,3], N. Lopez-Villalobos[1], C.W. Holmes[1] , E.A. Comeron[2], K.A. Macdonald[4],T.N. Barry[1] and N.C. Friggens[5,6]

[1] Massey University, Institute of Veterinary, Animal and Biomedical Sciences, Private Bag 11-222, Palmerston North, 5301, New Zealand.

[2] Instituto Nacional de Tecnología Agropecuaria (INTA), AIPA, Ruta 34 Km 227, (2300) Rafaela, Argentina.

[3] Facultad de Ciencias Agrarias, Universidad Nacional del Litoral, Kreder 2805, (3080) Esperanza, Argentina.

[4] DairyNZ , Private Bag 3221, Hamilton, 3240, New Zealand.

[5]INRA UMR 791 Modélisation Systémique Appliquée aux Ruminants, 16 rue Claude Bernard, 75231 Paris, France.

[6]AgroParisTech UMR 791 Modélisation Systémique Appliquée aux Ruminants, 16 rue Claude Bernard, 75231 Paris, France.

Accepted in Animal

ABSTRACT

This animal simulation model, named e-Cow, represents a single dairy cow at grazing. The model integrates algorithms from three previously published models: a model that predicts herbage dry matter (DM) intake by grazing dairy cows, a mammary gland model that predicts potential milk yield, and a body lipid model that predicts genetically driven live weight (LW) and body condition score (BCS). Both nutritional and genetic drives are accounted for in the prediction of energy intake and its partitioning. The main inputs are herbage allowance (kg DM offered/cow/day), metabolisable energy and neutral detergent fibre concentrations in herbage and supplements, supplements offered (kg DM/cow/day), type of pasture (ryegrass or lucerne), days in milk, days pregnant, lactation number, BCS and live weight at calving, breed or strain of cow and genetic merit (potential yields of milk, fat and protein). Separate equations are used to predict intake for herbage allowance expressed at the different cutting heights used in different countries. The e-Cow model is written in Visual Basic programming language within Microsoft Excel®. The model predicts whole-lactation performance of dairy cows on a daily basis, and the main outputs are daily and annual DM intake, milk yield, and changes in BCS and live weight. In contrast to other models, neither herbage DM intake, nor milk yield or LW change are needed as inputs, instead they are predicted by the e-Cow model. The e-Cow model was validated against experimental data for Holstein-Friesian cows with both North American (NA) and New Zealand (NZ) genetics grazing ryegrass pastures, with or without supplementary feeding and for three complete lactations, divided into weekly periods. The model was able to predict animal performance with satisfactory accuracy, with concordance correlation coefficients of 0.81, 0.76 and 0.62 for herbage DM intake, milk yield and live weight change, respectively. The e-Cow model tended to over-estimate milk yield of NA genotype cows at low milk yields (4.1 kg at milk yields of 12 kg/cow/day), whilst it under-estimated milk yield of NZ genotype cows at high milk yields (4.2 kg at milk yields of 27 kg/cow/day). The approach used to define the potential milk yield of the cow and equations used to predict herbage DM intake make the model applicable for predictions in countries with temperate pastures.

INTRODUCTION

Three of the most important challenges faced when simulating the performance of grazing dairy cows are: i) the prediction of herbage dry matter (DM) intake (Delagarde & O'Donovan, 2005), ii) the combination of nutritional and genetic mechanisms controlling energy partitioning within the cow (Friggens *et al.*, 2004) and iii) the inclusion of genetic differences between cows in the prediction of both herbage DM intake and energy partitioning (Bryant *et al.*, 2005). Few mathematical simulation models address all these challenges simultaneously.

The prediction of herbage DM intake at grazing is complex because of the characteristics of the swards and animals, and the biological processes involved in food selection, ingestion and digestion. The present study proposes an approach to predict intake based on an easy-to obtain set of inputs, combining theoretical and empirical equations that account for physical (rumen fill), metabolic (energy demand) and ingestive restrictions. This approach is fully described in Chapter 5.

The prediction of the energy allocated to either milk outputs or body lipid reserves, i.e., energy partitioning, is a long-standing problem that has not been solved. Traditionally, nutritional models approach nutrient partitioning within the cow as a homeostatic function of changing nutritional environment, solving divergences between nutrient intakes and milk outputs by adjusting body fat reserves up or down (Friggens and Newbold, 2007). However, coordinated changes in metabolism of body tissues, necessary to support a physiological state, were also recognised in dairy cows. The mechanisms explaining these changes, which occur as a function of (physiological) time rather than as a function of changing nutritional environment, were defined as homeorhetic mechanisms (Bauman and Currie, 1980). Thus, an aspect of nutrient partitioning is genetically driven and therefore, nutrient partitioning will change throughout lactation according to the genotype of the cow, and cannot be predicted only from feed intake and milk outputs (Friggens and Newbold, 2007).

Few nutritional models incorporate genetic differences between cows (Bryant *et al.*, 2005), and even less are adapted to grazing dairy cows. Bryant *et al.* (2008) developed a model that predicts the performance of dairy cows at grazing and accounts for genetic differences between cows. This model was validated for cows in early lactation, with acceptable accuracy of prediction for milk yield, but with low accuracy of prediction for herbage DM intake and live weight (LW) change.

The objectives of the present study are: i) to develop an animal model by integrating a nutritional model that predicts DM intake at grazing with two genetically driven models, one that predicts milk yield and the other that predicts body lipid changes, ii) to validate the animal model with a dataset from cows of different genetic merit grazing a forage diet, with and without concentrate supplementation and iii) to simulate animal performance under different feeding scenarios to explore the effects of genotype by environment, *i.e.*, nutrition, sensitivity of the integrated animal model.

Major efforts have been devoted to the development and validation of simulation models that predict DM intake, milk yield or body lipid changes separately for dairy cows. Therefore, it is important to integrate these models to represent more accurately the priorities and performance of dairy cattle. The integrated model, named e-Cow, is a dynamic and mechanistic model that bases its calculations on metabolisable energy (ME), works on a daily basis and can predict the whole lactation performance.

MATERIALS AND METHODS

Model overview

The current model, named e-Cow, integrates three previously published models: i) a model that predicts herbage DM intake for grazing dairy cows (Baudracco *et al.*, 2010a), hereafter named INTAKE model; ii) a mammary gland model (Vetharaniam *et al.*, 2003) that predicts potential milk yield, hereafter named MILK model and iii) a body lipid model (Friggens *et al.*, 2004) that predicts genetically driven live weight and body condition score, hereafter named LIPID model. Therefore, e-Cow predicts, on a daily basis, herbage DM intake, milk yield, and changes in body condition score (BCS) and LW for grazing dairy cows.

The rationale of e-Cow is that total metabolisable energy (ME) consumed (*MEItkTotal,* ME consumed from herbage plus supplements), calculated with the INTAKE model must be equal to the sum of all ME requirements (Equation 1), namely: ME for maintenance (ME_m) and pregnancy (ME_p) (Freer *et al.*, 2007); ME for growth in the case of young animals (ME_{gr}) (SCA, 1990); ME required for milk synthesis (*ME*

Potential Milk Yield) (see MILK model description below) and ME mobilised or synthesised from/to body lipid reserves (*ME from/to BCS change*) (see LIPID model description below). Both *ME Potential Milk Yield* and *ME from/to BCS change* represent the milk synthesis and BCS change genetically driven, which are later adjusted by the nutritional status of the cow as explain below.

$$MEItkTotal = MEm + MEp + MEgr + ME\ Potential\ Milk\ Yield + ME\ from/to\ BCS\ Change \quad (1)$$

The difference between ME intake and all the ME requirements is named *ME Balance*, and can be obtained by rearranging Equation 1, as follows:

$$ME\ Balance = MEItkTotal - (MEm + MEp + MEgr + ME\ Potential\ Milk\ Yield + ME\ from/to\ BCS\ Change) \quad (2)$$

Equations 1 and 2 integrate, in a mathematical sense, the INTAKE model, which provides the amount of energy consumed (pasture plus supplements), with the MILK and LIPID models, which provides the potential milk yield and BCS change, respectively, if no nutritional limitations occur. However, *ME Balance* will differ from zero when nutritional limitations occur, as it is usually the case in grazing dairy systems. In order to integrate the three models, *ME Balance* must be equal to zero. If *ME Balance* is less than zero, then an iterative procedure is used to reduce *ME Potential Milk Yield* and increase BCS loss (or decrease BCS gain) each by 1% of itself, until *ME Balance* is set to zero. A schematic overview of the model is depicted in Figure 1. Further details are given in Appendix 1. The e-Cow model is written in Visual Basic programming language within Microsoft Excel®.

The extent to which *ME from/to BCS change* and *ME Potential Milk Yield are* adjusted in the iteration depends on the stage of lactation, because they are adjusted each time within the iteration as a proportion (1%) of their initial predictions. The initial predictions comes from the LIPID and MILK models (explained below), and depends upon the stage of lactation.

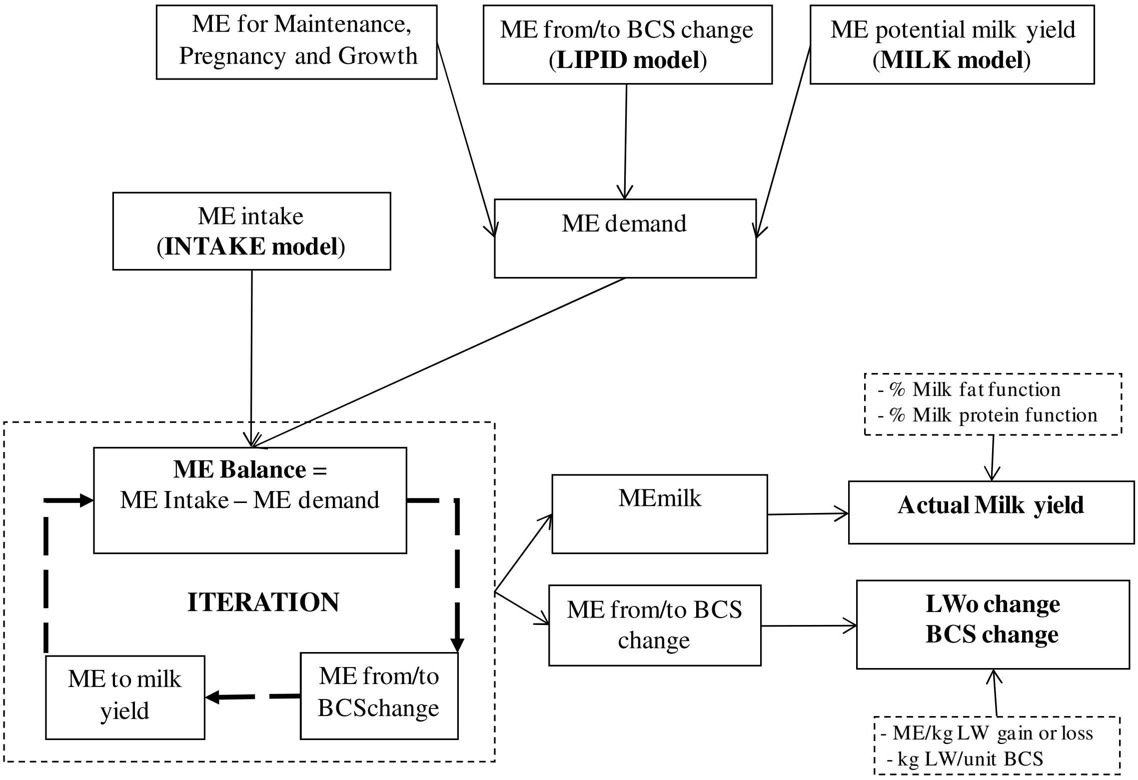


Figure 1 Schematic representation of the e-Cow model, showing the integration of INTAKE, MILK and LIPID models to predict metabolisable energy (ME) partitioning within the cow. LWo change = LW change associated with BCS change.

Prediction of dry matter intake - INTAKE model

The INTAKE model initially predicts herbage DM intake of grazing dairy cows, and then the total DM and total ME intakes if supplements are used. The model sets an upper limit to potential herbage *DM* intake at grazing (*PotDMI*) for cows offered only pasture, which is the minimum out of three limits: i) Physical limitation related to rumen fill (*PotDMIr*), ii) Metabolic limitation related to energy demand (*PotDMIe*) and iii) A 'grazing limit' related to ingestive constraints (*PotDMIg*). Detailed description of the three limits to potential DM intake can be found in Baudracco *et al.* (2010a).

To calculate the physical limit related to rumen fill (PotDMIr), the following parameters are considered: LW, herbage neutral detergent fibre (NDF) and the effect of stage of lactation on maximum ruminal capacity.

The metabolic limit to intake (*PotDMIe*) is calculated as follows:

$$PotDMIe\ (kg\ DM/cow/day) = MEReq\ /\ PastME \qquad (3)$$

where *MEReq (MJ ME/cow/day)*=

$$MEm + MEp + MEgr + ME\ Potential\ milk\ Yield + ME\ from/to\ BCS\ Change \qquad (4)$$

where *PastME* is the ME content of herbage (MJ ME/kg DM).The ME_m, ME_p, ME_{gr} are all defined above (Equation 1). For *ME from/to BCS change* and *ME Potential Milk Yield* see LIPID and MILK models, described below.

The grazing limit (*PotDMIg*) is set at 37.5 g herbage *DM* intake per kg LW times a coefficient accounting for the effect of stage of lactation on maximal ruminal capacity. This value of 37.5 g DM intake/kg LW is based on maximum intakes measured for high yielding HF cows grazing with no pasture quality or quantity restrictions (Kolver & Muller, 1998). However, this limit can be modified through the input screen described below under the title 'input and outputs screens of the e-Cow model', to represent the situation of a particular breed or strain.

Then, the minimum of these three *PotDMI* limits and the herbage allowance (kg DM/cow/day) are used to predict herbage *DM* intake for cows offered only pasture by using empirical algorithms (Equations 5 to 7). Those algorithms are derived from un-supplemented treatments in experiments with cows grazing ryegrass-based pastures or lucerne-based pastures. From those treatments, the ratio *HA*/*PotDMI* was calculated and regressed against the measured harvesting efficiency (*HE*), *i.e.*, efficiency of grazing. The empirical equations obtained from those regressions are used to predict harvesting efficiency and actual herbage DM intake of cows offered only pasture (Equations 5, 6 and 7). The equation obtained for ryegrass-based pasture with allowance expressed at ground level is (Baudracco *et al.*, 2010a):

$$HE\ (\%) = 57.676\left(\frac{HA}{PotDMI}\right)^{-0.536} \qquad (5)$$

while the equation obtained for ryegrass-based pasture with allowance expressed at a cutting height of 4 cm above ground level, derived from experiments detailed in Table 1 of Baudracco *et al*. (2010b), is:

$$HE\ (\%) = 83.37\left(\frac{HA}{PotDMI}\right)^{-0.7} \tag{6}$$

and for lucerne-based pastures, with allowance expressed at 4 cm above ground level; the equation is (Baudracco *et al.,* 2006):

$$HE\ (\%) = -0.322\ Ln\left(\frac{HA}{PotDMI}\right) + 0.7128 \tag{7}$$

Then, herbage DM intake (of cows offered only pasture) is obtained by multiplying *HE* times *HA*. When supplements are offered, the herbage DM intake of cows offered supplements (*HerbDMIs)* is calculated as:

$$HerbDMIs = HerbDMIo - SR\ x\ SupplDMI \tag{8}$$

where *HerbDMIo* is the herbage DM intake for cows offered only pasture. Substitution rate (SubR) expresses the decrease in kg DM intake of herbage per kg DM intake of supplement (*SuppDMI*), and it is calculated as follows:

$$SubR = 0.21\ HDMI - 0.18;\ (Stockdale,\ 2000) \tag{9}$$

where HDMI is herbage DMI before supplementation, expressed as kg DM/100kg LW.

Overall, the INTAKE model requires the following inputs: LW, days in milk (*DIM*), days pregnant, potential milk yield (from the MILK model), ME from/to BCS change (from LIPID model), herbage allowance, ME and neutral detergent fibre (NDF) concentrations in herbage and supplements and supplements offered (kg DM/cow/day).

Prediction of milk yield - MILK model

The *ME Potential milk yield* is calculated using a mathematical mammary gland model (Vetharaniam *et al.*, 2003), which is based on the interaction of two pools of alveoli (*i.e.,* groups of secretory cells), one active pool and one non-active pool. In this model, the amount of ME required to achieve the potential milk yield of a cow is calculated with the following equation:

$$\text{ME Potential milk yield (MJ ME/day)} = \text{SE}^{\text{L}}\left(\text{de}^{-\text{k2 t}} + \text{l6 e}^{\text{w6 t}} + \text{l7 e}^{\text{w7 t}}\right)/\text{Kl} \quad (10)$$

where *S* is the maximum milk secretion rate of active alveoli, *t* is the time after calving (days), *E* is the energy status at day *t* (set to 1 to calculate *ME Potential milk yield,* no nutritional limitations), *L* is a genetic parameter that governs the response of milk yield to nutrition (constant for each genotype, see Table 1), and *d*, k_2, *l*6, *w*6, *l*7, *w*7 are parameters related to the alveolar dynamic, *i.e*., number of active, quiescent and senescent alveoli (Table 1). Detailed explanation about the latter parameters and the alveolar dynamic can be found in Vetharaniam *et al.* (2003). As shown in Equation 11, *Kl* is a coefficient accounting for the efficiency of utilisation of ME for milk synthesis.

$$Kl = (MEdiet\ x\ 0.02) + 0.4 \quad (11)$$

where *MEdiet* is the weighted average energy content of feeds consumed (MJ ME/kg DM).

In the e-Cow model, *ME Potential milk yield* is estimated using the parameters reported by Vetharaniam *et al.* (2003) for first lactation cows of both New Zealand (NZ) Holstein-Friesian (HF) and North American (NA) HF strains offered total mixed ration (TMR) diets (no nutritional limitations). The constant *S* was re-parameterised for mature cows offered TMR diets, based on results reported by Kolver *et al.*(2002). The adjusted potential yield of mature cows (305-day lactation) after re-parameterisation are 11,247 and 8,011 kg milk per cow and 836 and 679 kg milksolids per cow for NA and NZ HF strains, respectively. These are default values of potential milk yield internally stored in the model. However, they can be modified if a different potential milk yield is set as input, or if an immature cow (less than 4 lactations) is simulated.

When the input 'potential milk yield' differs from the internally stored values, *i.e.*, 11,247 and 8,011 kg milk/cow for NA and NZ HF strains, an iterative procedure is used to find the value of the parameter *S* that produces a lactation curve with the new potential milk yield (kg milk for 305 days). An age-production factor is used to adjust potential milk yield for young cows. Multiplicative age adjustment factors for milk yields are: 0.75, 0.87, 0.95, 1.0, 0.97 and 0.92 for lactations 1, 2, 3, 4 to 7, 8 and 9, respectively (Lopez-Villalobos *et al*., 2000).

In the iterative procedure shown in Figure 1, *ME Potential Milk Yield* is converted into *MEmilk*, the latter being the ME available for *Actual Milk Yield.* Then, *MEmilk* is divided by *MElitre* to calculate *Actual Milk Yield* (litres/cow/day). The *MElitre* is the ME required to synthesise one litre of milk, and is calculated as the net energy content of milk (Freer *et al.,* 2007) divided by *Kl* (Equation 12).

$$MELitre = (0.0376\ x\ PercMilkFat + 0.0209\ x\ PercMilkProt + 0.948)/Kl \quad (12)$$

Percentages of milk fat (*PercMilkFat*) and percentage of milk protein (*PercMilkProt*) are required to calculate the energy content of milk. Lactation curves for milk fat and milk protein contents are modelled using the Wilmink (1987) function:

$$y_t = a + be^{-0.05t} + ct \quad (13)$$

where y_t represents the percentages of milk fat or milk protein at day *t* of lactation and *e* is the base of the natural logarithm (2.718281828), while *a*, *b* and *c* are parameters that define the shape of the curve. The values for parameters *a*, *b* and *c* were obtained from Roche *et al*. (2006), for both NZ and NA HF cows. Parameters *a*, *b* and *c* are adjusted in the e-Cow model according to the amount of concentrate in the diet, based on parameters reported by Roche *et al*. (2006) for cows offered different amount of concentrates. Examples of predicted concentrations of milk fat and milk protein by the e-Cow model, for cows consuming either 0 or 6 kg DM/cow/day concentrate, are given in Figure 2.

Table 1 Default parameters used in the e-Cow model to predict potential milk yield (MILK model), body lipid change genetically driven (LIPID model) and herbage intake (INTAKE model) for New Zealand and North American Holstein-Friesian (HF) cows.

Model		Parameter	New Zealand HF	North American HF	Reference
		S ($\times 10^{-9}$)	4.029	4.572	1
MILK		L ($\times 10^{-1}$)	5.78	5.07	1
		k2 ($\times 10^{-1}$)	1.116	1.525	1
	Potential	D ($\times 10^{9}$)	-9.614	-8.903	1
	Milk	w6 ($\times 10^{-4}$)	-9.907	-5.099	1
	Yield	w7	-5.943	-5.884	1
		l6 ($\times 10^{10}$)	2.642	2.742	1
		l7 ($\times 10^{9}$)	1.093	1.107	1
	Milk fat	*a*	3.685	2.76	2
	curve (%)	*b*	2.62	2.8	2
		c	0.0049	0.00451	2
	Milk	*a*	3.072	2.94	2
	Protein	*b*	1	1.1	2
	Curve (%)	*c*	0.00337	0.0035	2
LIPID		BCS day T 1st	3.00	2.75	3
		BCS day T 2nd	2.90	2.65	3
		BCS day T >2	2.85	2.60	3
		BCS next calving	3.30	3.05	3
		MaxLipLoss[5]	-1.75	-1.75	4
INTAKE		Metabolic limit based on potential ME requirements, which depends on potential milk yield and genetically driven BCS change.			

1 Vetharaniam *et al*. (2003), with constant S re-parameterised for mature cows offered TMR diets from Kolver *et al*. (2002).
2 Wilmink function parameters reported by Roche *et al*. (2006).
3 Assumtions based on Firggens *et al*. (2004) and results from (Horan *et al*., 2005; McCarthy *et al*., 2007).
4 Values proposed by Friggens *et al*. (2004).
5 MaxLipLoss is a maximal rate of lipid loss (kg/day) (Friggens *et al.,* 2004).

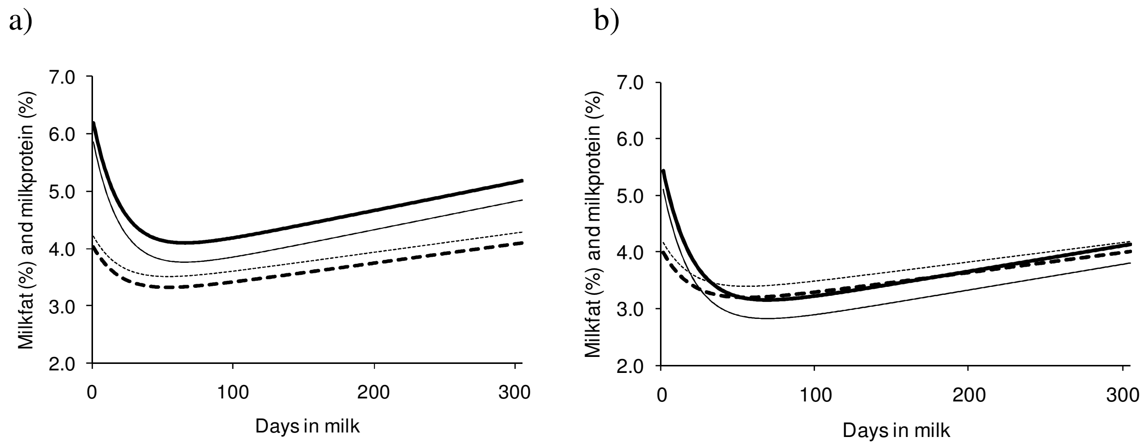


Figure 2 Example of predicted concentration of milk fat and milk protein throughout lactation for (a) New Zealand Holstein-Friesian cows and (b) North American Holstein-Friesian cows. Milk fat content for cows consuming either 0 (▬) or 6 (—) kg DM/cow/day concentrate. Milk protein content for cows consuming either 0 (---) or 6 (.....) kg DM/cow/day concentrate.

Prediction of body condition score and live weight - LIPID model

The model proposed by Friggens *et al.* (2004) is used to predict the genetically driven pattern of body lipid change throughout pregnancy and lactation. This LIPID model is based on evolutionary arguments suggesting that at any given time in pregnancy and lactation there is an optimal level of body fatness that the animal is genetically driven to accomplish.

The LIPID model proposes that mobilisation and gain of body reserves are genetically driven to achieve two target levels of body fatness, one at, or around, conception and another at the next calving. Thus, cows in good body condition at calving will allocate large amounts of their energy reserves and energy intake towards milk yield, reducing their BCS to achieve the target level of fatness at conception. In contrast, cows at a low BCS at calving will adjust mechanisms of nutrient partitioning and lipogenesis to increase BCS, to attain the target genetic level of fatness at conception. After conception, the model predicts that cows will gradually increase body condition in order to meet the target BCS at next calving. As explained below, this target BCS at next calving depends upon the genetic merit of the cow.

Assumptions of the LIPID model

1. The cow is driven to have a target amount of body lipid mass (L, expressed in kg) at a particular time in lactation (T, expressed as days from calving). The T value used is 112 DIM.
2. The rate of body lipid change, dL/dt (kg/d), changes linearly with time between calving and day T.
3. If pregnant, the cow is driven to have a specific amount of lipid at the next calving, called Lnext (kg).
4. The rate of change of body lipid (dL/dt) changes linearly with time between conception and the next calving.
5. At times greater than T, and if the cow is not pregnant then dL/dt is assumed to be 0, *i.e.*, the cow has no drive to increase body lipid mass.
6. There is a maximal rate of lipid loss, called MaxLipLoss (kg/day). This is a negative value of dL/dt.

There are further assumptions and adjustments for this model that can be found in Friggens *et al.* (2004).

Estimation of Body Lipid Mass from LW and BCS

Body lipid mass at calving is calculated as the product of empty body weight and the proportion of lipid in the empty body. To convert BCS (measured on a 0 to 5 scale) to body lipid proportion, the following equation is used (Friggens *et al.*, 2004):

$$\textit{Body lipid proportion (g/g of empty body)} = 0.12 \times (\textit{Condition score} - 0.36) \quad (14)$$

Empty body weight can be calculated from LW (standardised for condition score) and from estimates of gut fill (Appendix 1). The LIPID model assumes that the LW associated with a unit change BCS is 12.9% of LW at BCS 5 and that gut fill is 15% of LW at BCS 3.

The inverse relationships are used to calculate BCS from body lipid mass and LW_0 change (LW change associated with BCS change). Further details of the LIPID model can be found in Friggens *et al.* (2004). In summary, the inputs required by the LIPID model are BCS and LW at calving, and the date of conception (days after calving). The default parameters used in the model are listed in Table 1.

The LW_0 change (LW change due to changes in BCS) and BCS change are calculated using the ME associated with BCS change (*ME from/to BCS Change*) resulting from the iteration (Figure 1), the ME required to synthesise/mobilise 1 kg LW and the kg of LW per unit of BCS. The energetic cost associated with LW_0 change (MJ ME per kg LW gain or LW loss) is calculated based on the equations proposed by AFRC (1990) (see Appendix 1).

It is important to notice that the LIPID model predicts only the genetically driven changes in BCS and LW_0, and assumes no nutritional constraints. However, when integrated into the e-Cow model, LW_0 and BCS changes depend upon the nutritional status of the cow, given that *ME from/to BCS change* is recalculated in the iteration (see Figure 1), and adjusted according to the *ME Balance* of the cow. For example, after conception the LIPID model predicts that cows will gradually increase BCS to meet the target BCS at next calving, however, the iteration introduces a nutritional component and therefore, the e-Cow model will predict that the cow loses BCS after conception, if energy intake is very low.

Figure 3 shows an example of the original BCS curve predicted with the LIPID model, and two BCS curves for either low or high nutritional levels when the LIPID model is integrated into the e-Cow model.

Input and outputs screens of the e-Cow model

Figure 4 shows the Visual Basic interface screens developed for the e-Cow model. In the 'cow inputs' tab of Figure 4a, by defining the genotype of the cow and the lactation number, the default values from Table 1 will be used to estimate potential yields of milk, fat and protein. The e-Cow model calculates the potential milk fat and milk protein yields (kg/cow in 305-day lactation), by multiplying the daily percentages of milk fat and milk protein by the daily potential milk yield, and then summing the milk fat and milk protein yields for the whole lactation. These calculated potentials can be modified by using a different potential fat and protein yields as input (kg/cow in 305-day) (Figure 4a, ‘cow inputs’ tab, ‘genetic merit of the cow’). If the potential yields are modified, then, an iterative procedure is used to find a new value for the parameter *a* of the Wilmink function for the curves of milk fat and milk protein percentages, to obtain the new potential yields of milk fat and milk protein (305 days in milk) set as inputs. Furthermore, parameters of Table 1 can be manually changed by selecting the buttons LIPID model, MILK model and INTAKE model parameters in the ‘cow inputs’ tab.

Lactation can be stopped at any stage by setting a dry-off policy (Figure 4a, Dry-off Policy), defining a threshold value for either BCS or milk yield or the number of days before next calving date. When any of this threshold values is achieved, the lactation will be finished. The BCS at calving can be set using the US or NZ system, and conversions between systems are calculated according to Roche *et al.* (2009) (Appendix 1).

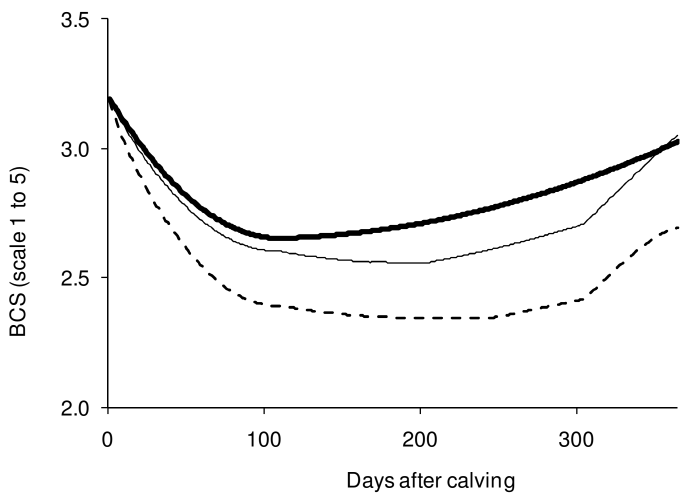
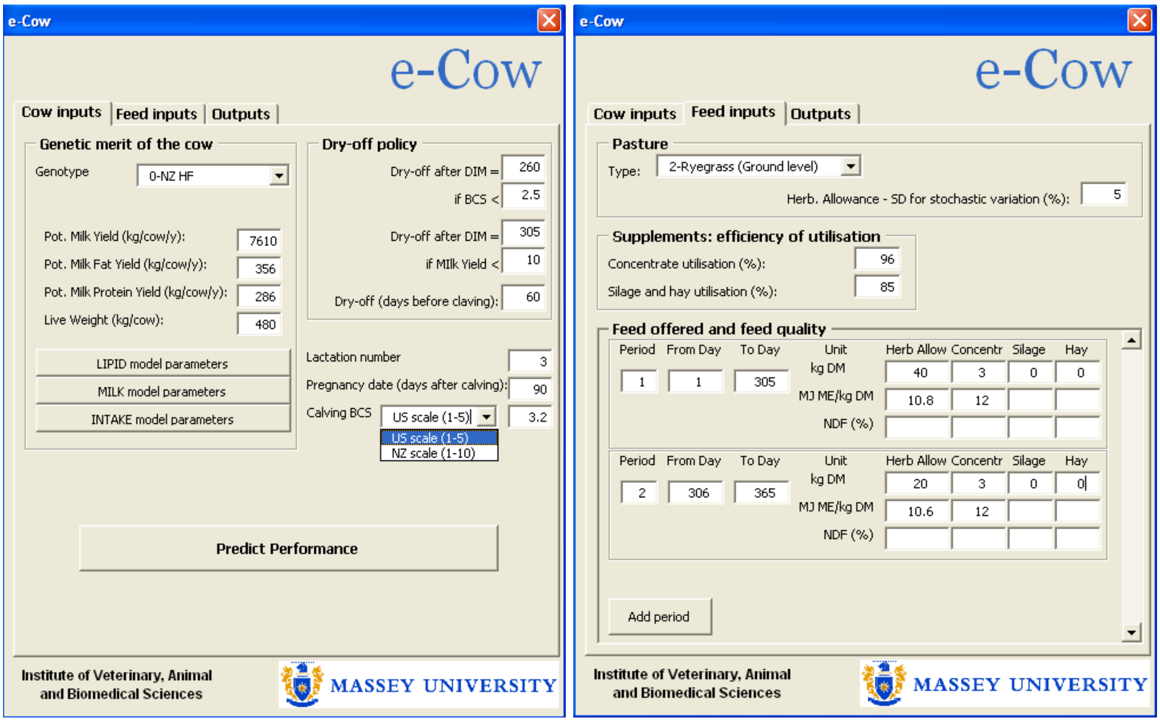


Figure 3 Example of BCS curves predicted with (**━**) the LIPID model (Friggens *et al*, 2004) and with the e-Cow model for North American HF cows offered either pasture plus 6 kg DM concentrates (—) or only-pasture diet (- -). Example for cows in second lactation, offered herbage allowance of 50 kg/cow/day, with 11.0 MJ/kg DM herbage.

a)



b)

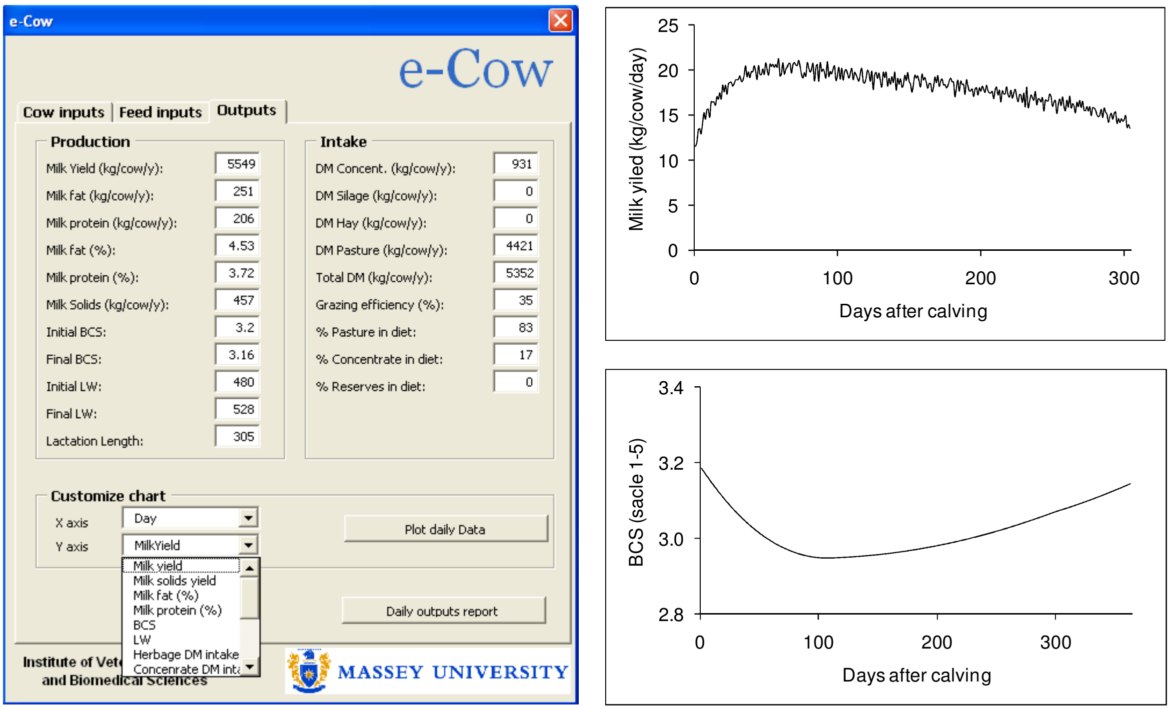


Figure 4 Visual Basic interface screens of e-Cow inputs (a) and outputs (b). The charts appear when clicking on 'plot daily data' button in the 'customised chart' section of the output screen (b).

In the 'feed inputs' tab (Figure 4a), by defining the type of pasture, the pertinent equation (5, 6 or 7) will be used to predict herbage DM intake at grazing. Then, in the same tab, the amounts, ME and NDF contents of pasture and supplements offered can be defined, for as many periods as desired. Daily herbage allowance can be simulated stochastically (with normal distribution), with the mean being the input value of pasture allowance per period and the SD being the input value set as 'herb. allowance SD for stochastic variation' expressed as a percentage of the mean herbage allowance (Figure 4a, 'feed inputs' tab).

The 'outputs' tab (Figure 4b) shows a summary of annual production and intake variables, and allows customised charts to be plotted with the daily values for the whole lactation for the main output variables. The 'daily output report' bottom will show a table with the daily values of all the output variables.

Energy requirements for maintenance, pregnancy and growth

The e-Cow model assumes that requirements for maintenance, growth and pregnancy are satisfied before all other requirements.

Maintenance

The ME required for maintenance (ME_m) is calculated as follows (Freer *et al.*, 2007):

$$MEm\ (MJ/day) = \frac{1.4(0.28 \times LW^{0.75} \times EXP(-0.03 \times A)}{Km} + 0.1 \times ME\ milk + \frac{Egraze}{Km} \qquad (15)$$

where *A* is the age in years, *km* is the net efficiency of use of ME for maintenance calculated as: 0.02 *MEdiet* + 0.5, *MEdiet* is the weighted average ME concentration of the feed available (MJ/kg DM), *MEmilk* is the amount of dietary ME being used directly for milk production and *Egraze* is the additional energy expenditure of a grazing animal compared with a similar housed animal (Freer *et al.*, 2007) (see Appendix 1). The value of *MEm* is required to calculate *MEmilk* (see Figure 1) and, therefore, this creates a circular calculation. To solve this, the *MEmilk* of the previous day is used in Equation 15. When using Visual Basic programming language, the use of *MEmilk* of the day before is made possible by referring to 'day-1', since each variable is defined as an array with 365 elements (days). Thus, the value of the previous day is defined as 'day-1'.

Pregnancy

Gestation length is assumed as 284 days. Requirements of ME to maintain pregnancy (*MEp*) are calculated using the standard equations proposed by SCA (1990) (see Appendix 1).

Growth

Metabolisable energy required for growth of cows is calculated as (SCA, 1990):

$$MEgr = LWgr \ \times EVg \tag{16}$$

where *LWgr* is the LW gain per day due to growth (see Equation 18) and *EVg* is the ME value per kilogram of LW gain, which is calculated as:

$$EVg\ (MJ\ ME/kg) = \frac{1.3\left(4.1+0.0332\ x\ LW - 0.000009\ x\ LW^2\right)}{(1-0.1475\ x\ LWgr)} \tag{17}$$

Live weight change due to growth

The LW gain due to growth (LW_{gr}) of young animals must be included in the final calculation of LW change. The e-Cow model assumes that cows in their first, second and third lactation will grow to ensure target LW at maturity. The LW gain due to growth is calculated on the basis of the difference between target weights at two consecutive lactations. It is assumed that target weights (*Target LW*) post calving are 85%, 92% and 96% of mature weight for cows in first, second and third lactation, respectively (Fox *et al*., 1999). These values are set as default in the model. The daily growth is assumed to be linear between lactations, and is calculated as follows:

$$LWgr\ (kg/day) = (Target\ LWnext - \ Target\ LW)/365 \tag{18}$$

where *Target LWnext* and *Target LW* are the postcalving *LW* at the next and present lactation, respectively.

Live weight change due to pregnancy

The LW change predicted with the LIPID model represents only the LW associated with body lipid reserves (LW_0). For pregnant animals, LW gain due to growth of the gravid uterus (LW_p) should be added to predicted daily LW_0 change. It can be calculated as follows (Fox *et al.*, 1999):

$$LWp\ (kg/day) = (CBW\ x\ (18.28\ x\ 0.02 - 0.0000286\ x\ \ t)\ x\ e^{(0.02 \times t - 0.0000143 \times t \times t))} \qquad (19)$$

where *CBW* is the calf birth weight in kg, *t* is the time pregnant (days), *e* is the base of the natural logarithm (2.718281828).

Validation of the e-Cow model

Validation determines whether the mathematical model is an accurate representation of the real system. Parameters and equations used to build the e-Cow model were obtained from Friggens *et al.* (2004), Vetharaniam *et al.* (2003), Baudracco *et al.* (2006; 2010a,b), Kolver *et al.* (2002), Roche *et al.* (2006), Horan *et al.* (2005) and McCarthy *et al.* (2007).

An independent dataset was obtained from a trial that evaluated three strains of HF cows grazing ryegrass-clover pasture in NZ (Macdonald *et al.*, 2008). The two strains used in the validation of e-Cow were NA HF 90s (NA90; ≥ 91% North American genetics) and NZ HF 90s (NZ90; ≤ 24% North American genetics). The dataset comprised information about 60 cows of each of these two strains, over three full lactations (1st, 2nd and 3^{rd} parities). Data used as input in e-Cow were: days in milk, days pregnant, BCS at calving, LW at calving, lactation number, herbage allowance, supplements DM intake, herbage NDF, herbage ME content and supplements ME content. All data were averaged across week of lactation for each of the three parities, resulting in 135 points for validation in each of the two strains.

The concordance correlation coefficient (Lin, 1989) and the relative prediction error (Fuentes-Pila *et al.*, 2003) were used to evaluate the extent of agreement between actual and predicted values. The concordance correlation coefficient (CCC) is calculated as: CCC = $\rho \times C_b$, with ρ the Pearson correlation coefficient and C_b the bias correction factor, which is calculated as:

$$C_b = 2\,\sigma_A \sigma_P / (\sigma^2_A + \sigma^2_P + (\mu_A - \mu_P)^2) \quad (20)$$

where σ_A, μ_A, σ_P and μ_P are the SD and mean of the actual and predicted values, respectively. The Pearson correlation coefficient reflects precision, *i.e.*, degree to which the predicted against actual values cluster about the regression line. The bias correction factor reflects accuracy, *i.e.*, degree to which the regression line adheres to the 45° line through the origin. The scale of Landis and Koch (1977) has been used here to describe the degree of concordance, with: 0.21–0.40 being “Fair”; 0.41–0.60 being “Moderate”; 0.61–0.80 being “Substantial”; and 0.81–1.00 being “Almost perfect”.

The relative prediction error (RPE) is defined as the positive square root of the mean square prediction error (MSPE, Equation 21), expressed as a percentage of the mean of the actual values (μA) (Fuentes-Pila *et al.*, 2003).

$$MSPE = \frac{1}{n}\sum_{i=1}^{n} (Ai - Pi)^2 \quad (21)$$

where *P* represents the predicted values and *A* represents the actual observed values for either herbage DM intake, milk yield or LW change. Fuentes-Pila *et al.* (1996) suggested that a RPE value lower than 10% is an indication of satisfactory prediction, whereas a RPE between 10% and 20 % indicates a relatively acceptable prediction, and a RPE greater than 20% indicates poor prediction.

RESULTS

Model validation

Comparison of predicted and observed data (the whole dataset averaged per week of lactation) show that the e-Cow model was able to simulate lactation curves of similar shape to the observed data for herbage DM intake, milk yield and LW change (Figure

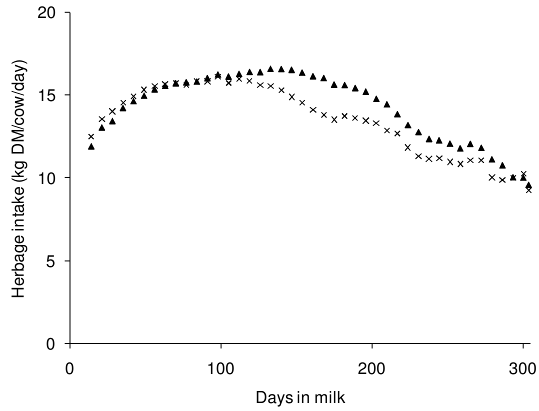
5). Predictions of herbage DM intake were very close to observed data, with a slightly overestimation in mid and late lactation (Figure 5a). Milk yield was underestimated in early lactation and overestimated in mid and late lactation (Figure 5b). Predictions of LW change were generally higher than observed, but under predicted for the first weeks of lactation (Figure 5c).

Further validation analysis for individual cow strains, and for each parity within strain, showed satisfactory accuracy of prediction, with RPE lower than 10% for herbage DM intake and between 10 and 20% for milk yield and with CCC over 0.80 for herbage DM intake, over 0.70 for milk yield and over 0.60 for LW change (Table 2 and Figure 6).

Predicted data were plotted against observed data for each of the two strains for herbage DM intake, milk yield and LW change (Figure 6). Average prediction of herbage DM intake was 0.9 kg DM and 0.4 kg DM higher than observed for NA and NZ HF cows, respectively (Table 2). Differences between average predicted and observed milk yield (kg milk/cow/day) were +3.0 kg and -0.6 kg for NA and NZ HF cows, respectively (Table 2), with a trend towards over prediction at low milk yields and under predictions at high milk yields in both strains, which was more noticeable for NZ HF cows (Figure 6e).

Live weight change predictions were less accurate than herbage DM intake and milk yield predictions, with over predictions at both extremes, low and high LW changes. Differences between average predicted and observed LW change were +0.09 and +0.10 kg/cow/day for NA and NZ HF cows, respectively (Table 2).

a)



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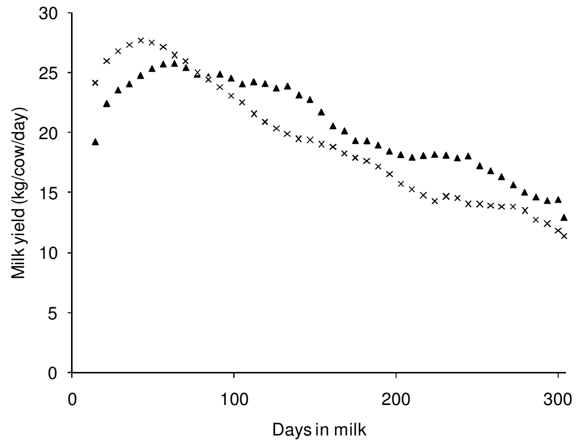

c)

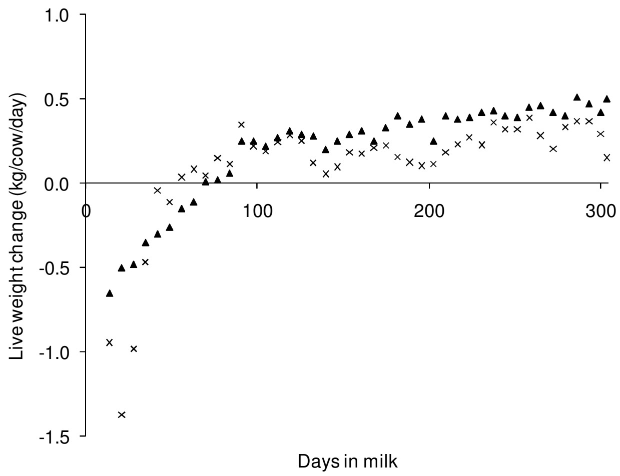

Figure 5 Comparison between predicted (▲) and actual data (x) for (a) herbage dry matter intake, (b) milk yield and live weight change (c). Actual data was obtained from Macdonald *et al.* (2008), and comprises information of three parities of Holstein-Friesian cows for both New Zealand and North American strains. The whole dataset was averaged per week of lactation.

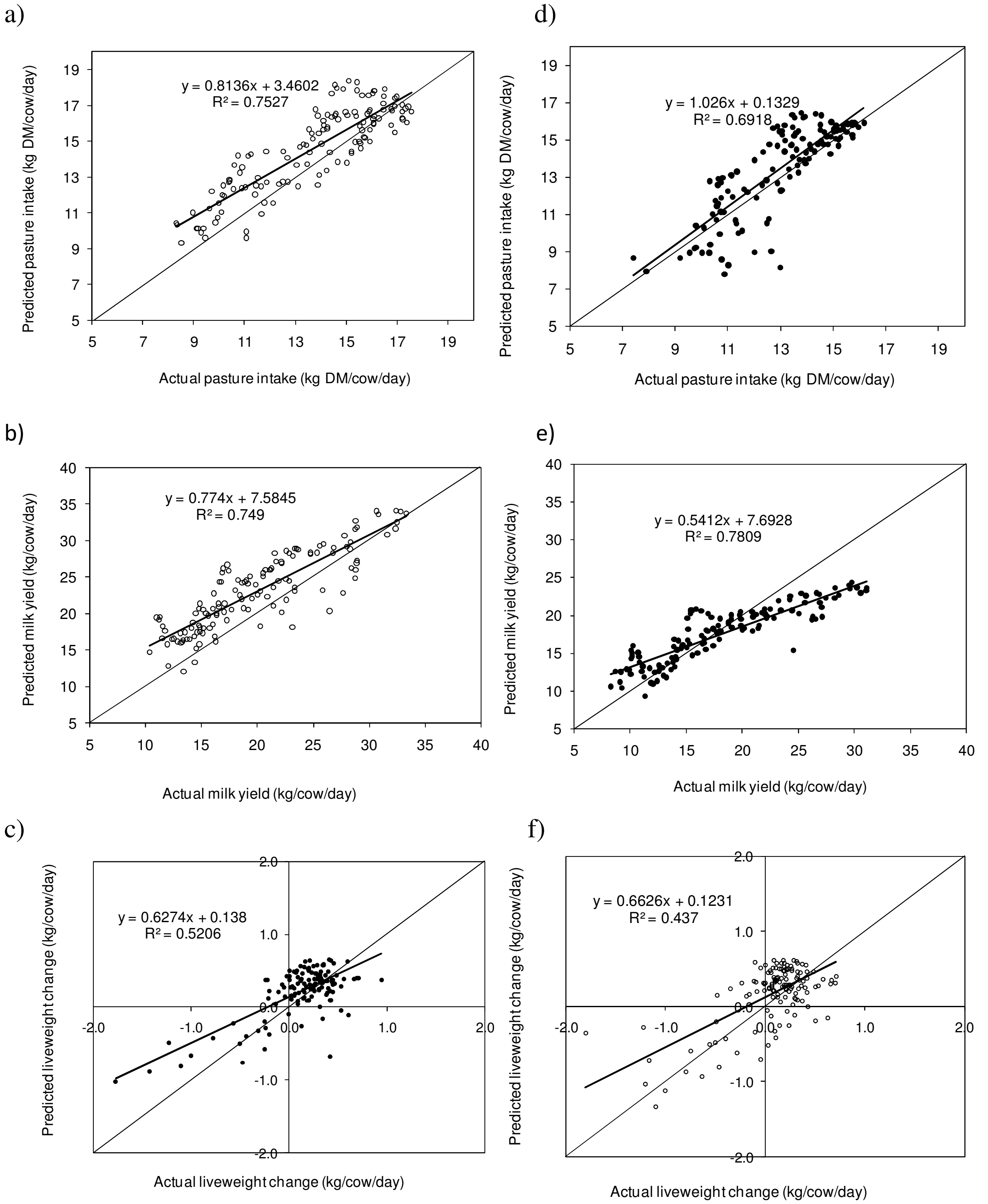

Figure 6 The relationship between predicted and actual values for herbage DM intake (kg DM/cow/day), daily milk yield (kg/cow/day) and LW change (kg/cow/day) of North American (a, b, c) and New Zealand (d, e, f) Holstein-Friesian cows. Actual values obtained from a strain trial dataset (Macdonald *et al.*, 2008) including data from 60 cows of 1st, 2nd and 3rd parity for each strain. Values averaged across week of lactation for each parity.

Table 2 Comparison of actual (Macdonald et al., 2008) and predicted (e-Cow) data for daily yields of milk (kg/cow), daily herbage dry matter (DM) intake (kg/cow) and daily live weight (LW) change (kg/cow). The validation dataset includes data from North American (n=60) and New Zealand (n=60) Holstein-Friesian cows of 1st, 2nd and 3rd parity. Data were averaged across week of lactation for each strain and parity and then analysed.

	Herbage DM intake		Milk yield		LW change	
	NAHF	NZHF	NAHF	NZHF	NAHF	NZHF
Actual	13.7	13.0	19.9	18.0	0.08	0.11
Predicted	14.6	13.4	22.9	17.4	0.17	0.21
R	0.87	0.83	0.85	0.87	0.64	0.69
RPE	9.1	9.8	15.4	18.0	NA	NA
CCC	0.81	0.80	0.74	0.77	0.61	0.63

R = Pearson correlation coefficient, RPE = Relative prediction error, CCC = Concordance correlation coefficient. NA = Not available.

Model simulations

The simulated curves of milk yield and BCS throughout lactation for both NZ and NA HF cows at two levels of feeding (0 and 6 kg DM concentrates/cow/day) can be observed in Figure 7. At the same stage of lactation, milk yield (kg milk/cow/day) was higher for NA HF than for NZ HF cows, and the milk response to supplementation was greater for NA than for NZ cows (Figure 7a). Body condition score curves differed between and within strain for different feeding levels (Figure 7b). Thus, NA HF cows could not recover the calving BCS, even when supplemented with 6 kg concentrates. In contrast, simulations for NZ HF cows showed that this strain achieved a BCS at next calving of 3.1 and 3.5 when offered 0 and 6 kg concentrate/cow/day, respectively (Table 3 and Figure 7b). Furthermore, Figure 7b shows how the e-Cow model is also sensitive to the energy status of the cow, accounting not only by genetic but also by nutritional drives, as the nutrition level affected the evolution of BCS throughout lactation.

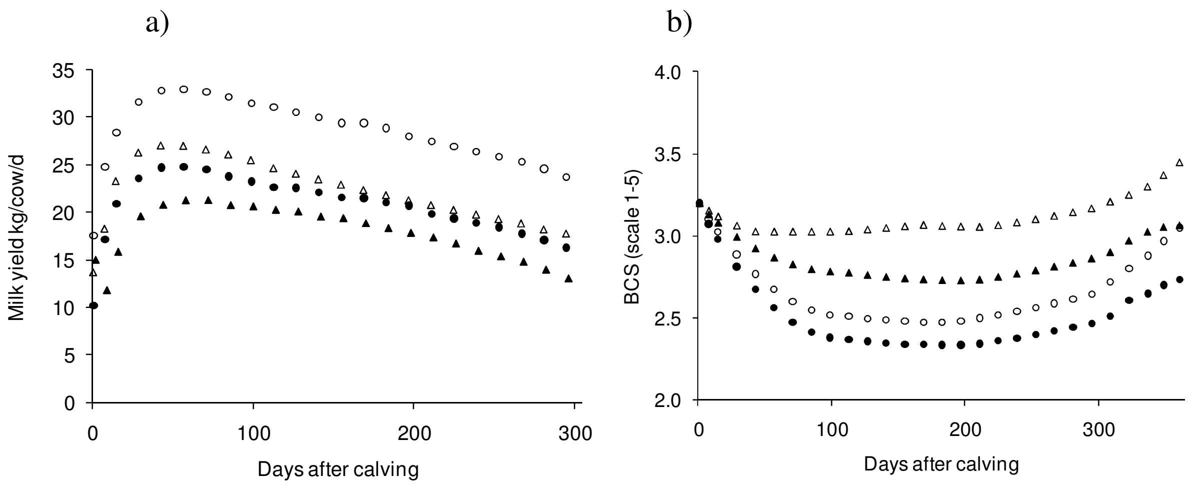

Figure 7 Model simulations of milk yield (a) and body condition score (BCS) (b) during lactation for North American Holstein-Friesian cows consuming 0 kg (●) or 6 kg DM/cow/day concentrate (○); and for New Zealand Holstein-Friesian cows consuming 0 kg (▲) or 6 kg DM/cow/day concentrate (∆). Example for cows in second lactation, offered herbage allowance of 50 kg/cow/day, with 11.0 MJ/kg DM herbage, and concentrates with 12.0 MJ/kg DM.

Two BCS curves were simulated for each strain of HF cows by defining BCS at calving at either 2.8 or 3.2 as inputs (Figure 8). This simulation shows the way in which BCS is genetically driven to the target BCS (BCS T and BCS at next calving, Table 1) set for each strain as it is conceptualised in the LIPID model (Friggens *et al.*, 2004). Thus, when calving at BCS 2.8, NZ HF cows, with a target BCS T (around conception) of 2.90 will minimise mobilisation of lipid reserves in order to achieve their target, whereas NA HF cows have scope to mobilise lipid reserves, as their genetic target BCS T is set at 2.65 (Table 1).

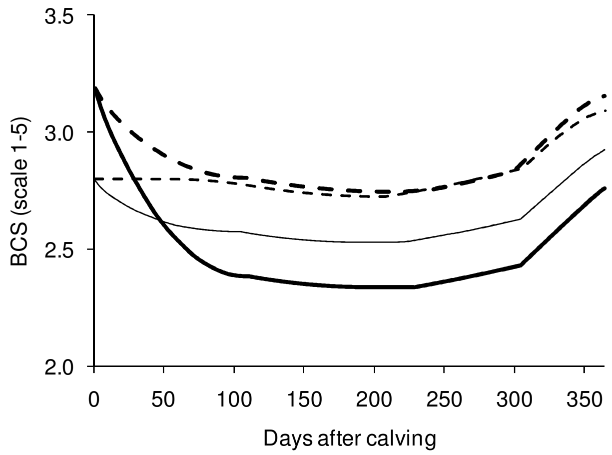

Figure 8 Model simulations of BCS during lactation for North American Holstein-Friesian (▬ and —) and for New Zealand Holstein-Friesian cows (▬ ▬ and - - -), calving with a BCS of either 3.2 or 2.80 (1 to 5 scale). Example for cows in second lactation, offered herbage allowance of 50 kg/cow/day, with 11.0 MJ/kg DM herbage, and offered no concentrates.

A genotype by environment interaction occurs when animals differ in their ability to perform in different environments (Falconer, 1981). Simulations depicted in Table 3 show that the e-Cow model is sensitive to genotype by environment interactions in regards to milksolids yield and milk yield. At low levels of feeding, i.e., no concentrates offered, both strains performed similarly in terms of milksolids yield (kg MS/cow/lactation), but when 6 kg DM concentrate were offered, i.e., higher level of feeding, NA HF produced more milksolids, as a consequence of their higher potential milk yield. The increment in milk yield as feeding level increased was also higher for NA HF than for NZ HF cows (Table 3). These results agree with results from Kolver et al. (2005), who compared both HF strains under feeding conditions similar to those used in the simulation shown in Table 3.

Table 3 Model simulations of milk yield, milksolids yield (fat plus protein) and BCS during lactation for North American (NAHF) and New Zealand Holstein-Friesian NZHF) cows consuming 0 kg or 6 kg DM/cow/day of concentrate. The example is for cows in their second lactation (460 and 530 Kg LW for NZHF and NAHF), with calving BCS of 3.2, offered herbage allowance of 50 kg/cow/day, with 11.0 MJ/kg DM herbage, and concentrate with 12.0 MJ/kg DM.

	0 kg concentrate		6 kg concentrate	
	NAHF	NZHF	NAHF	NZHF
Milk yield	6 400	5 456	8 923	6 856
Milksolids yield	451	450	618	555
BCS 305 days	2.7	2.9	3.1	3.2

DISCUSSION

The e-Cow model allows the prediction of a dairy cow's performance at grazing with and without supplementary feeding. The main features of the e-Cow model are its satisfactory accuracy of prediction, the prediction of whole-lactation performance on a daily basis, the use of physical, metabolic and ingestive constraints in the prediction of herbage DM intake and the homeostatic and homeorhetic control of body lipid change. In addition, the e-Cow model is able to predict performance of cows of different genetic merit and is able to account for genotype by environment interactions. It uses an easy-to-obtain set of inputs and it is presented with an accessible user inputs screen.

Model validation

In validation tests, the e-Cow model showed satisfactory accuracy of prediction for herbage DM intake, milk yield and LW change, and it compared well to the accuracy of prediction reported for similar models. Two other models, the animal model MOOSIM (Bryant *et al*., 2008) and the whole-farm model WFM (Beukes *et al.*, 2006; Beukes *et al.*, 2008), both described in Table 4, were validated with the same dataset as the e-Cow model, but in all three cases, validation points were different. The WFM was validated for each HF strain separately and the validation points were annual values averaged per herd (3 years), the MOOSIM model was validated including both NA and NZ strain in the same dataset and the validation points were daily values of individual cows in early lactation (1 year), while the e-Cow model was validated for each HF strain and for each parity separately, and the validation points were weekly values for the whole lactation (3 years).

The accuracy of prediction was higher for the e-Cow model (Table 2) than for MOOSIM, the latter having CCC of 0.59, 0.27 and 0.16 for milk yield, DM intake and LW change, respectively. The WFM reported a RPE of 11% for milk yield, which is more accurate than that obtained for milk yield with the e-Cow model (Table 2).

There was a trend towards under predictions of milk yield at high milk yields for NZ HF cows (Figure 6e). This bias comes from the parameters used to define the potential lactation curve (Table 1), which set a lower potential milk yield for NZ HF cows than for NA HF cows.

Prediction of herbage intake, milk yield and body condition score

The e-Cow model predicts herbage DM intake at grazing (it is not an input), on a daily basis, for individual cows and does not need expected milk yield or expected LW change as inputs (Table 4). The prediction of herbage DM intake in the e-Cow takes into account physical, metabolic and ingestive constraints to intake. From the models summarised in Table 4, only MOOSIM, WFM, CAMDAIRY and GrazeFeed can predict herbage DM intake at grazing and do not need milk yield or LW change as inputs. Some of the models summarised in Table 4 were designed for indoor feeding systems. A further difference between the e-Cow and other models for grazing dairy cows is that the e-Cow predicts the whole-lactation performance at once, while other models predict one day at a time (CAMDAIRY, DietCheck). The ability to predict the whole lactation performance with the e-Cow model gives a more holistic approach of the effect of the genetic merit of the cow and the feeding environment on the cow's performance.

As shown in Table 4, the only models that account for genetic drives (homeorhetic control) to predict BCS changes are the MOOSIM model, the model reported in Martin & Sauvant (2007) and the WFM and the e-Cow model. This is an important strength of these models over models driven only by nutritional factors. However, in the e-Cow model and Friggens *et al*. (2004), the parameters defining the initial genetically driven BCS curve (BCS, T and BCS next calving) used for different strains and parities require further testing.

The genetic merit of the cow in the e-Cow model is defined by her potential yields of milk, fat and protein, LW and parameters shown in Table 1 for BCS targets. This is an original way to define the genetic merit of the cow. The strength of this approach is that the model can be used for varying conditions across different countries, whereas in the case of using breeding values to define the genetic merit of the cow, the model is limited to the conditions in the country where BVs were estimated. A particular feature of this approach is that, by increasing the potential yields of the cow, DM intake will not increase if the feed offered is restricting intake (quantity or quality), as usually happens in grazing systems. Increments in the potential yields of the cow will only effect increments in DM intake when the metabolic limit is restricting intake, *i.e*., the potential of the cow rather than the diet is limiting milk yield.

In the e-Cow model, the BCS of the cow affects DM intake at grazing, inasmuch as it affects the metabolic limit of potential DM intake (as deduced from Equation 4). For example, assuming cow A and B are the same and both the physical (*PotDMIr*) and grazing limits (*PotDMIg*) to intake are higher than the metabolic limit (*PotDMIe*), if cow A loses more BCS, the e-Cow predicts that cow A will have a lower intake than cow B.

As explained in the methodology section, the approach used here to define potential yields in the e-Cow model was based on productions achieved by healthy cows under experimental conditions, where feed quantity and quality were not limiting (no major nutritional limitations). However, this does not mean that the actual genetic merit of the cow is known, but it is a pragmatic approach to define potential genetic merit. The model uses default parameters (Table 1) to define the genetic potential of the cow, however, a different cow can be defined by changing those parameters (using the buttons 'LIPID model parameter', etc). The e-Cow model was validated against a dataset of cows grazing ryegrass-based pastures, however, the equations used to predict herbage DM intake of lucerne-based pastures were previously validated with a dataset from cows grazing lucerne-based pastures (Baudracco *et al*., 2006).

Model simulations

The greater simulated milk response to concentrates by NA HF cows compared to that of NZ HF (Figure 7) is consistent with independent experimental data (not used to develop or validate the e-Cow model) showing that high energy demanding cows (high proportion of NA genes) have a greater response to supplements (Fulkerson *et al.*, 2008; Kennedy *et al.*, 2003; Kolver *et al.*, 2005). This illustrates an important feature of e-Cow, which is its genotype by environment sensitivity.

Reasons for greater milk response to supplements in NA HF cows compared to NZ HF cows are that NA HF have a higher relative feed deficit when grazing pastures (Holmes & Roche, 2007; Penno *et al.*, 2006), and this results in a lower substitution rate. Additionally, as shown in Figure 7b, and reviewed elsewhere (Roche *et al.*, 2009), high energy demanding cows, *i.e*., NA HF cows, mobilise more energy from body lipid reserves in early lactation, which is available for milk synthesis, and partition a greater proportion of energy consumed towards milk yield in mid and late lactation (effected by using different parameters for each strain in the LIPID model). Thus, cows with superior genetics for milk production have a depressed BCS profile (Roche *et al.*, 2009), a consequence of the genetic correlation between these traits. Furthermore, the lower substitution rates predicted for NA HF cows occurred because the model sets a greater metabolic limit to intake for NA HF than NZ HF cows (PotDMIe), given the higher potential milk yield of the former (effected by using different parameters for each strain in the MILK model).

A web-based version of e-Cow is under development on the Massey University web site (Inputs and outputs screens shown in Appendix 2). This version will be valuable for applied research, teaching and extension purposes. In addition, e-Cow is being integrated into a stochastic, dynamic, whole-farm model named e-Dairy.

Table 4 Description of simulation models, summarising the main characteristics of the approach used to predict milk yield, live weight and dry matter intake. Some of the models summarised are whole-farm models, and some other are models developed to formulate rations.

	Simulation: Level and Frequency	Herbage intake predicted or input	Milk yield Predicted or input	Homeorhetic control of body lipid change	Parameters accounting for genetic differences
GrazFeed (Freer *et al*., 1997)	Cow Daily	Predicted	Predicted	No	Potential milk yield
Camdairy (Hulme *et al*., 1986)	Cow Weekly	Predicted	Predicted	No	Potential milk yield
UDDER (Larcombe, 1990)	Herd 10 Days	Predicted	Predicted	No	Potential milk yield
SIMCOW (Kristensen *et al*., 1997)	Cow Daily	Predicted	Predicted	No	Potential milk yield
DAFOSYM (Rotz *et al*., 1999)	Herd Daily	Predicted	Predicted	No	Potential milk yield
CNCPS (Fox *et al*., 2004)	Cow Daily	Predicted	Predicted based on peak milk yield as input	No	Peak milk yield
WFM- Molly (Beukes *et al*., 2006)	Cow Daily	Predicted	Predicted	Yes	Mature peak daily milk (MPDM) using a mammary gland model.
DietCheck (Heard *et al*., 2004)	Cow Daily	Predicted	Set as input. Predicts milk response to supplements	BCS change set as input	Milk yield
MOOSIM (Bryant *et al*., 2008)	Cow Daily	Predicted	Predicted	Yes	Estimated breeding values and reaction norms
Martin & Sauvant (2007)	Cow Daily	Uses an empirical model to create standard intake and lactation curves		Yes	Potential milk yield
Vetharaniam & Davis (2006)	Cow Daily	Input	Predicted	No	Potential milk yield
Karoline (Danfar *et al*., 2006)	Cow weekly	Input	Predicted	No	Breeding values and reaction norms from yields of milk, fat and protein and DM intake
MDSM (Shalloo *et al*., 2004)	Herd Monthly	From database		No	From database
e-Cow	Cow Daily	Predicted	Predicted	Yes	Potential milk, fat and protein yields, BCS and LW parameters

Limitations of the e-Cow model

The e-Cow model is based on metabolisable energy requirements, and it does not account for protein requirements. In addition, at the current stage of development, it does not include the effects of the environment, *i.e.*, weather conditions, on the performance of the cow. Future developments could include sward parameters, such as pre-grazing HM, in the prediction of herbage DM intake.

The accuracy of prediction of the e-Cow may decrease for diets with less than 50% of pasture and high quality supplements, because the potential DM intake is initially set for a whole-pasture diet. The prediction of BCS changes for the whole lactation, performed with e-cow, agrees with published data for each of the two HF strains. However, the e-Cow model may not be accurate in the prediction of short-term changes in BCS across lactation. In addition, the dataset used for validation of e-Cow had a reduced range of supplementation levels, and, therefore, predictions for cows offered high levels of supplements may not be as accurate as those for cows offered low levels, as it may underestimate DM intake at high supplementation levels

At the current stage of development, the e-Cow model does not relate pregnancy rate to BCS, but it could be linked in future work, by associating probabilities of pregnancy to levels of BCS.

CONCLUSIONS

The main strength of the e-Cow model is its ability to predict, on a daily basis, herbage DM intake, milk yield and changes in BCS and LW for dairy cows at grazing, accounting for genetic differences between cows and with higher accuracy compared to other models. In contrast, most of animal models for dairy cows are designed for cows fed under indoor conditions, where feed intake can easily be measured. Furthermore, most of the other models either require intake or milk yield as inputs, or predict body lipid change only driven by nutritional factors , or do not account for genetic differences between animals.

The e-Cow model was able to reproduce the differences observed in experiments for two strains of HF dairy cows, including the interaction between strains of HF cows and environment, *i.e.*, nutrition. The approach used to define the potential milk yield of the cow and the equations used to predict herbage DM intake at grazing should allow the use of e-Cow in many countries with temperate pastures.

ACKNOWLEDGEMENTS

The authors thank Marcelo Zamateo for his support in the development of this model.

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Chapter 7

e-Dairy: a dynamic, stochastic, whole-farm model that predicts physical and economic performance of grazing dairy systems

J. Baudracco[1,3], N. Lopez-Villalobos[1], C.W. Holmes[1] E.A. Comeron[2], K.A. Macdonald[4] and T.N. Barry[1]

[1] *Massey University, Institute of Veterinary, Animal and Biomedical Sciences, Private Bag 11-222, Palmerston North, 5301, New Zealand.*

[2] *Instituto Nacional de Tecnología Agropecuaria (INTA), AIPA, Ruta 34 Km 227, (2300) Rafaela, Santa Fe, Argentina.*

[3] *Facultad de Ciencias Agrarias, Universidad Nacional del Litoral, Kreder 2805, Esperanza, CP: S3080HOF, Argentina.*

[4] *DairyNZ , Private Bag 3221, Hamilton, New Zealand.*

To be submitted to Animal

ABSTRACT

A whole-farm simulation model for grazing dairy systems was developed. The model is stochastic, dynamic, is written in Visual Basic programming language within Microsoft Excel®, and includes a user-friendly interface screen. It has an energy-based animal module that integrates algorithms to predict intake, mammary gland functioning and body lipid change. Both nutritional and genetic drives are accounted for in the prediction of energy intake and its partitioning in the animal module.

This whole-farm model is original because it simulates individual cows, randomly generated on the basis of variance and co-variances from experimental datasets, and is able to simulate stochastically and simultaneously some of the key dairy system variables including pasture grown, genetic merit of cows, milk price and supplement price. Its versatility in terms of defining calving patterns, *i.e.*, any weekly pattern, type of pasture, *i.e.*, ryegrass-based or lucerne-based, and genetic merit of cows makes the model useful for different types of grazing dairy systems.

The main inputs of e-Dairy are farm area, use of land, type of pasture, type of crops, monthly pasture growth rate, supplements offered, nutritional quality of feeds, herd description including herd size, age structure, calving pattern, body condition score (BCS) at calving, live weight (LW) at calving, probabilities of pregnancy, average genetic merit: potential yields of milk, fat and protein, and economic values for items of income and costs. The model allows the user to set management rules such as dry-off policy, *i.e.*, ceasing of lactation, target pre and post-grazing herbage mass (HM), a policy to make hay or silage from pasture, and supplementation. The main outputs are herbage dry matter (DM) intake, annual pasture utilisation, milk yield, changes in BCS and LW, economic farm profit and return on assets.

In validation analyses using two datasets from farmlet systems experiments, the model showed satisfactory accuracy of prediction, with relative prediction errors lower than 10% for all variables, and concordance correlation coefficients over 0.80 for annual pasture utilisation, yields of milk, fat and protein, and of 0.69 and 0.48 respectively for live weight and body condition score at the end of the 365-day period. The model can be used to explore the effects of feeding level and genetic merit and their interactions for grazing dairy systems with differing calving patterns, evaluating the trade-offs between profit and the associated risk.

INTRODUCTION

System modelling involves the use of mathematical models to represent the key features of a system, in order to make inferences about the system (Woodward *et al.*, 2008). Thus, the modelling of dairy systems becomes a powerful tool to adjust the system in a context of changing market prices of milk and feeds, changes in policies and changes in the genetic merit of cows.

Components of cattle production systems are usually studied separately (Leon-Velarde & Quiroz, 2000). This reduction of the system into its parts frequently ignores interactions and can lead to the loss of vital information for the global analysis of the system (Congleton, 1984). Therefore, a whole-farm approach is required for an accurate representation of a real world situation. Furthermore, to evaluate the risk associated with management strategies, key dairy system variables *i.e*., genetic merit, market prices and pasture production, were allowed to behave stochastically.

Several whole-farm models simulate grazing dairy systems, namely, CAMDAIRY (Hulme *et al.*, 1986), UDDER (Larcombe, 1990), GrazFeed (Freer *et al.*, 1997), MDSM (Shalloo *et al*., 2004), WFM (Beukes *et al.*, 2008) and Farmax Dairy Pro (Bryant *et al*., 2010). However, the e-Dairy model, described in this study, differentiates from the aforementioned models in its capability to, simultaneously, simulate the performance of individual cows on a daily basis, and to account for stochastic variations on the genetic merit of the cow, pasture production, milk and supplement prices. In addition, the e-Dairy model predicts herbage intake, milk yield and changes in live weight accounting for genetic and nutritional drives, and is also sensitive to genotype by environment interactions.

The objectives of the present study are to describe and validate the e-Dairy whole-farm simulation model, and to demonstrate the use of the model with a stochastic simulation of a grazing dairy system. The e-Dairy model was designed to explore interactions between genetic merit, supplementation and stocking rate, and their impact on physical and economic performance of the system. Multiple runs can be performed to represent either different farms in one year or different years for the same farm.

MATERIALS AND METHODS

Model overview

The e-Dairy model is energy based, dynamic (daily simulation over 365-day period), and is written in Visual Basic programming language within Microsoft Excel®. Dairy farms with either ryegrass-based or lucerne-based pastures, and with any calving pattern can be simulated. An animal model, e-Cow (Baudracco *et al*., 2011a), was integrated into e-Dairy to simulate the performance of individual cows. Within e-Cow, both nutritional and genetic drives are accounted for in the prediction of metabolisable energy (ME) intake and its partitioning.

The main inputs of e-Dairy are farm area, use of land for either pasture and crops, type of pasture (ryegrass-based or lucerne-based), type of crops (winter or summer crop), monthly pasture growth rate (used to predict daily herbage mass (HM) for each paddock), supplements offered, quality of feeds including neutral detergent fibre (NDF) and ME, herd description including herd size, age structure, calving pattern, BCS at calving, probabilities of pregnancy, average genetic merit: potential yields of milk, fat and protein, and economic data for items of income and costs. The model allows the user to set management rules such as dry-off policy, target pre and post-grazing HM, a policy to make hay or silage from pasture, and supplementation. The main outputs are herbage DM intake, annual pasture utilisation, milk yield, changes in BCS and LW, economic farm profit and return on assets.

The e-Dairy model was designed to explore interactions between genetic merit, supplementation and stocking rate, allowing for stochastic behaviour of genetic merit, pasture production, milk price and supplement price.

Lactating and non-lactating cows are simulated in e-Dairy. Male calves are assumed to be sold at 5 days old and female calves are assumed to be reared off-farm. The surplus female calves can be sold or sent for rearing off-farm.

Cow module

Each cow has its own values for genetic merit and is simulated individually on a daily basis in e-Dairy, using the animal model e-Cow described in Baudracco *et al*. (2011a), which is an energy-based model that simulates a single dairy cow at grazing.

The e-Cow model predicts intakes of DM and energy, yields of milk, fat and protein, and changes in BCS and LW. The main features of the e-Cow model are the combination of physical, metabolic and ingestive constraints in the prediction of herbage DM intake, the homeostatic and homeorhetic control of body lipid change and its ability to predict performance of cows of different genetic merit.

The e-Cow model includes equations to predict herbage DM intake for ryegrass-based pasture when allowance is expressed 4cm above ground level (common in Europe), for ryegrass-based pastures with allowance expressed at ground level (common in Australia and New Zealand), and for lucerne-based pasture when allowance is expressed 4cm above ground level (common in Chile and Argentina). The genetic merit of the cow in the e-Cow model is defined by her potential yields of milk, fat and protein for a 305-day lactation period, and genetic targets for LW at calving, and BCS at conception and at next calving. The genetic potentials and genetic targets are those achieved by the cow when no feeding restrictions are imposed. Daily milkfat and milkprotein concentrations are calculated using the Wilmink (1987) function:

$$y_t = a + be^{-0.05t} + ct \quad (1)$$

where y_t represents the percentages of milk fat or milk protein at day t of lactation and e is the base of natural logarithm (2.718281828), while a, b and c are estimated parameters that define the scale and shape of the curve. Potential milk yield is calculated using a mathematical mammary gland model (Vetharaniam *et al.*, 2003), in which the amount of ME required to achieve the potential milk yield (*ME Potential Milk Yield*) of a cow is calculated with Equation (2). Further details are given in the description of the e-Cow model (Baudracco *et al.*, 2011a).

$$ME\ Potential\ Milk\ Yield\ (MJ\ ME/day) = SE^{\mathrm{L}}\left(\mathrm{d}e^{-\mathrm{k2}\ \mathrm{t}} + l6\ \mathrm{e}^{\mathrm{w6}\ \mathrm{t}} + l7\ e^{w7\ t}\right)/\ \mathrm{Kl} \quad (2)$$

The potential yields of fat and protein are the result of the sum of the product between daily potential milk yield and daily milkfat or milkprotein concentration. The BCS and LW are modelled according to the genetically driven body lipid change model proposed by Friggens *et al*. (2004), which proposes that mobilisation and gain of body reserves are genetically driven to achieve two genetic targets of body fatness, one at, or around, conception and another at the next calving. All equations used in the e-Cow model are described in detail in (Baudracco *et al*., 2011a).

Herd

Random generation of cows with correlated variables

Each cow is randomly generated through the following correlated variables: potential yield of milk, LW at calving and parameters of the Wilmink function defining milk fat and milk protein concentration curves (Equation 1). The values for parameters *a*, *b* and *c* of this function were obtained from Roche *et al*. (2006), for both NZ and NA HF cows. In order to randomly simulate a herd in which each cow has correlated values for all variables, this matrix operation is performed:

$$\boldsymbol{H} = \boldsymbol{m}' + \boldsymbol{L} \times \boldsymbol{Z} \quad (3)$$

where $\boldsymbol{H}$ is the matrix of the generated herd, with each trait in a column and each cow in a row, **m** is the vector with the herd mean values for each trait (input), $\boldsymbol{L}$ is the lower triangular matrix obtained by Cholesky decomposition of the phenotypic (co)variance matrix between the traits (potential yield of milk, LW at calving and parameters of the Wilmink function defining milk fat and milk protein concentration curves), and $\boldsymbol{Z}$ is a matrix with random values derived from a normally distributed function with a mean of 0 and a SD of 1.

Elements of the phenotypic (co) variance matrix were estimated using phenotypic records from a trial comparing cows of North American and New Zealand Holstein-Friesian strains (Macdonald et al., 2008b), and are presented in Appendix 3. This matrix, from which the $\boldsymbol{L}$ matrix is obtained, is used to reproduce the variance within traits and the correlation between traits. The product between the matrix $\boldsymbol{L}$ and $\boldsymbol{Z}$ creates the herd variance for each trait. The $\boldsymbol{m}$ vector contains all the traits described as columns of the H matrix, and represents the average values for each trait of the herd. This average values are set as default for each strain (reported in Chapter 6), but can be modified from the inputs screens shown in Figure 1.

In summary, the herd is defined in a matrix, in which columns are potential milk yield in a 305-day lactation period, LW at calving, parameters a, b and c of Wilmink function defining the shape of milkfat and milkprotein concentrations. Each cow is further allocated an age (see below) and BCS at calving. The BCS at calving is defined in the ‘cows’ input screen (Figure 1b, ‘initial BCS’), with a mean and a SD for a normal distribution, to randomly allocate a unique BCS at calving to each cow of the H matrix.

Age structure.

The age structure of the herd is defined in the ‘cows’ input screen (Figure 1b, ‘age structure’) as the percentages of cows in each age category, i.e., year. Then, each of the generated cows in the matrix H is randomly given an age. Afterwards, potential milk yield and LW are adjusted for each cow. The following multiplicative age adjustment factors are used to adjust potential milk yields: 0.75, 0.87, 0.95, 1.0, 0.97 and 0.92 for lactations 1, 2, 3, 4 to 7, 8 and 9, respectively (Lopez-Villalobos et al., 2000). Multiplicative age adjustment factors for LW at calving are: 0.85, 0.92, 0.96 for cows in first, second and third lactation, respectively (Fox et al., 1999).

Paddocks, pasture, crops and supplements

Paddocks with pasture

The number of paddocks with pasture is defined in the input screen (Figure 1a, ‘farm inputs’), as well as a common size for all paddocks. However, the size can be modified for each paddock. Additionally, a production factor between 0 and 1 can be given to each paddock, in order to account for differences in potential production due to the type and fertility level of soils. This production factor affects the pasture growth rate set as input. A value of 1 indicates that the net herbage growth rate of the paddock equals the value set as input, common to all paddocks. By default, all paddocks have a production factor equal to 1.

The net herbage accumulation rate of pasture on each paddock is unique, and depends on a general net herbage accumulation rate curve (monthly values given as inputs), which is affected by the particular HM of the paddock, which is altered by the events of grazing and its intensity (see herbage mass and herbage accumulation below).

Figure 2 show examples of the individual simulation of paddocks and cows. Graphs show the average, minimum and maximum value for each variable, however, the evolution of any particular cow or paddock can be requested to be plotted. Figure 2a gives an example of the grazing events across the simulation. In Figures 2a, 2b and 2c, the uniqueness of each randomly generated cow is depicted through the milk yield, milkfat and BCS patterns of each cow.

Paddocks with crops

The same approach used with pastures is used to define the number and size of both summer and winter crop paddocks. A menu is available to set the area of land used for cropping in the 'farm inputs' screen (Figure 1a). Initially there are two options: 'whole year crop' or 'seasonal crop'. In both options there is sub menu to define the number and size of paddocks, the type of crop (summer or winter), the amount of DM produced/ha/year, the fate of the crop (grazing, silage or hay) and the grazing/harvesting efficiency. If grazing is selected, the grazing efficiency is constant for all paddocks and for all the grazing events, in contrast to what happens in paddocks with pasture, where grazing efficiency is predicted for every paddock and every grazing event.

Within 'whole year crop', it is assumed that the same area is used with winter and summer crop. When the option 'seasonal crop' is selected, dates of start and final land used for either summer or winter crop need to be defined. Under this option, the period of time without crop is assumed to be with pasture.

Herbage mass, herbage accumulation and grazing dates

Net daily herbage growth rates are required as input, as average of each month. Pasture growth can behave stochastically or deterministically. For stochastic simulation, the input herbage growth is used as the mean of a normal distribution, and a SD is required as input, expressed as a percentage of monthly mean. For deterministic simulation the growth rates used are those set as inputs.

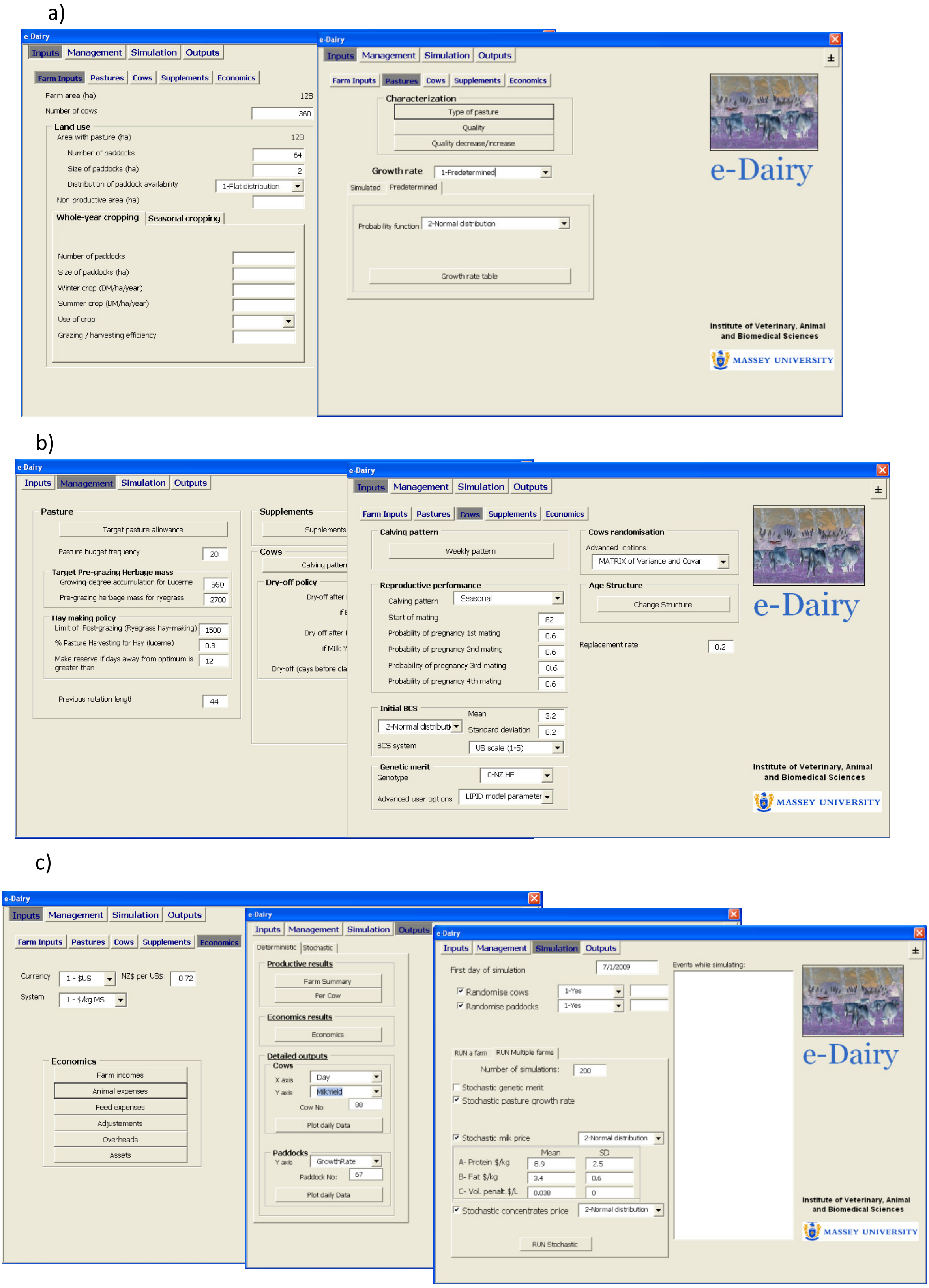

Figure 1 Visual Basic interface screens of e-Dairy model for (a) ‘farm inputs’ and ‘pasture’, (b) ‘management’ and ‘cows’ and (c) ‘economics’, ‘outputs’ and ‘simulation’ screens. Further details are given in Appendix 4.

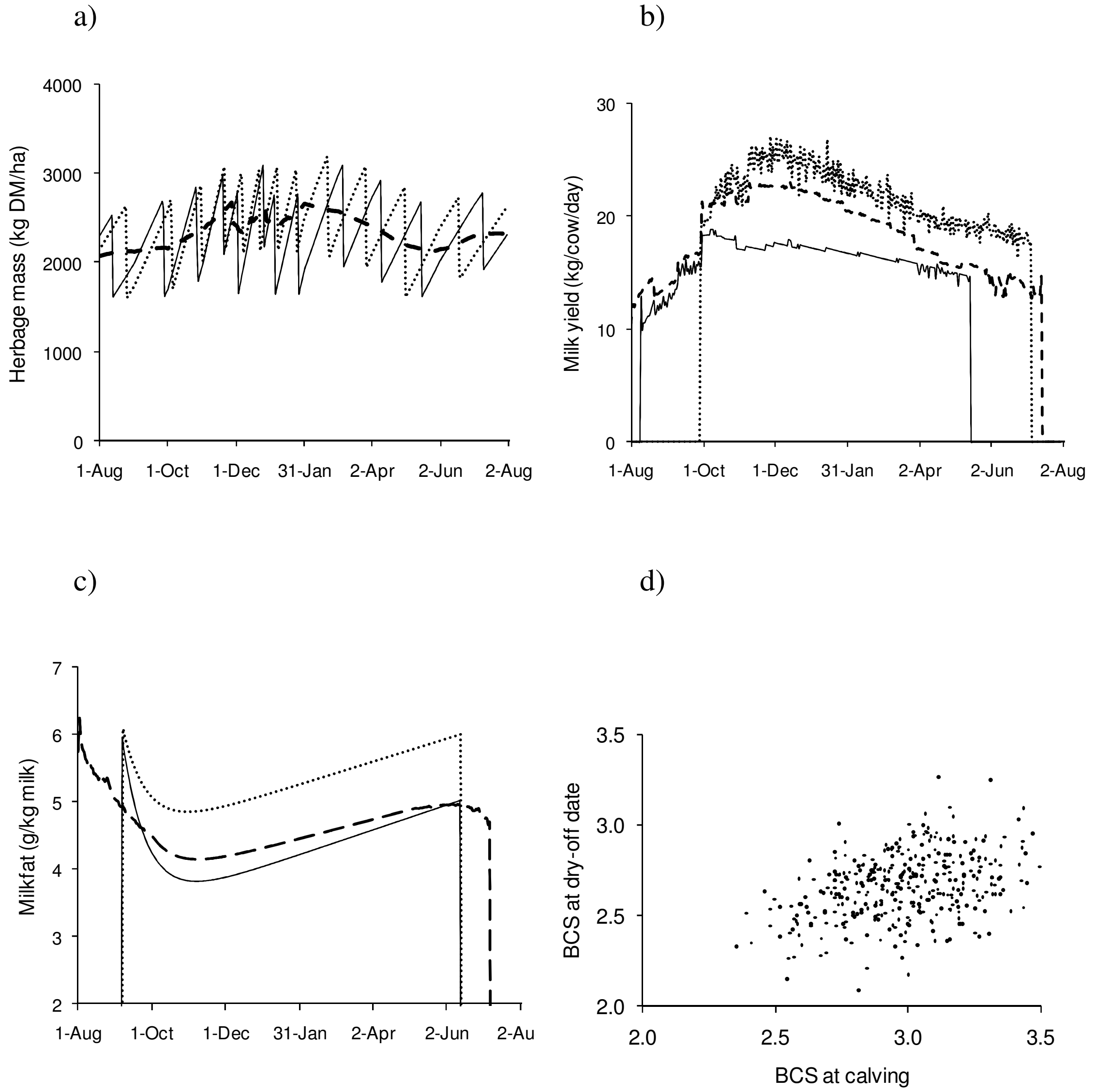

Figure 2 Simulation showing results for individual paddocks and individual cows. Herbage mass (a) in the paddock with minimum (—), maximum (….) and average (- - -) herbage mass (HM) across a 365-day period. Milk yield (b) and milkfat percentages (c) for cows with minimum (—), maximum (….) and average value across lactation (- - -). Body condition score (d) at the end of lactation (dry-off) as a function of body condition score (BCS) at calving for each simulated cow.

Before the simulation of the first day, an initial grazing date named 'previous grazing date' is allocated randomly to each paddock with pasture, by defining as input a 'previous rotation length'. Thus, if the 'previous rotation length' is set at 60 days, each paddock will be randomly allocated a 'previous grazing date' between 60 days before the first day of simulation and the first day of simulation, with a flat probability function. Herbage mass will accumulate from 'previous grazing date' until 'next grazing date' (explained below), starting with an amount of HM set with an input called 'target post-grazing HM' for ryegrass-based pastures, and starting with HM of zero for lucerne pasture because it is assumed that all the post-grazing HM is not available for next grazing.

An 'optimum grazing date' is calculated in the model as the date when HM reaches the 'target pre-grazing HM', which is an input defined in the 'management' screen (Figure 1b) as kg DM/ha for ryegrass based pastures and as the HM reached after certain 'growing-degree accumulation' for lucerne pastures. Daily minimum and maximum temperatures are needed to calculate 'growing-degree accumulation' for lucerne pastures.

The actual date of grazing, named 'next grazing date' may differ from the calculated 'optimum grazing date' (Figure 3) according to the use of paddocks defined by the pasture budget sub-routine (see pasture budget section below). The calculated difference between the 'optimum grazing date' and the 'next grazing date' is called 'days away from optimum', as shown in Figure 3. Herbage mass in each paddock will accumulate daily, from 'previous grazing date' until 'next grazing date', as show in the time line of Figure 3. This Figure is a representation of the internal calculations of the model, however, the user only need to set inputs shown in Figure 1a and 1b. The rate of pasture growth set as input is affected by the grazing intensity, using the following logistic Equation (Garcia, 2000):

$$\text{Pasture growth rate} = (\text{GR} \times \frac{4}{\text{HMmax}}) \times \text{ HM } (1 - \frac{\text{HM}}{\text{HMmax}}) \qquad (4)$$

where *GR* is the input growth rate (kg DM/day), *HM* is the HM of the paddock in the day of simulation, *HMmax* is the HM at which net accumulation rate approaches zero because senescence rate approaches gross growth rate. The *HMmax* is an input, with a default value of 4500. This function produces a sigmoid curve with an initial period of slow herbage accumulation for low HM, a period of accelerating herbage accumulation rate as HM approaches the optimum, followed by a period of deceleration of herbage accumulation toward the ceiling HM (*HMmax*) (Bircham & Hodgson, 1983). Thus, allowing herbage mass to exceed the optimum point, *i.e.*, delayed grazing, or grazing to below the optimum point, will reduce the growth rate. Response to fertiliser is not simulated, but could be indirectly included by changing the input growth rates.

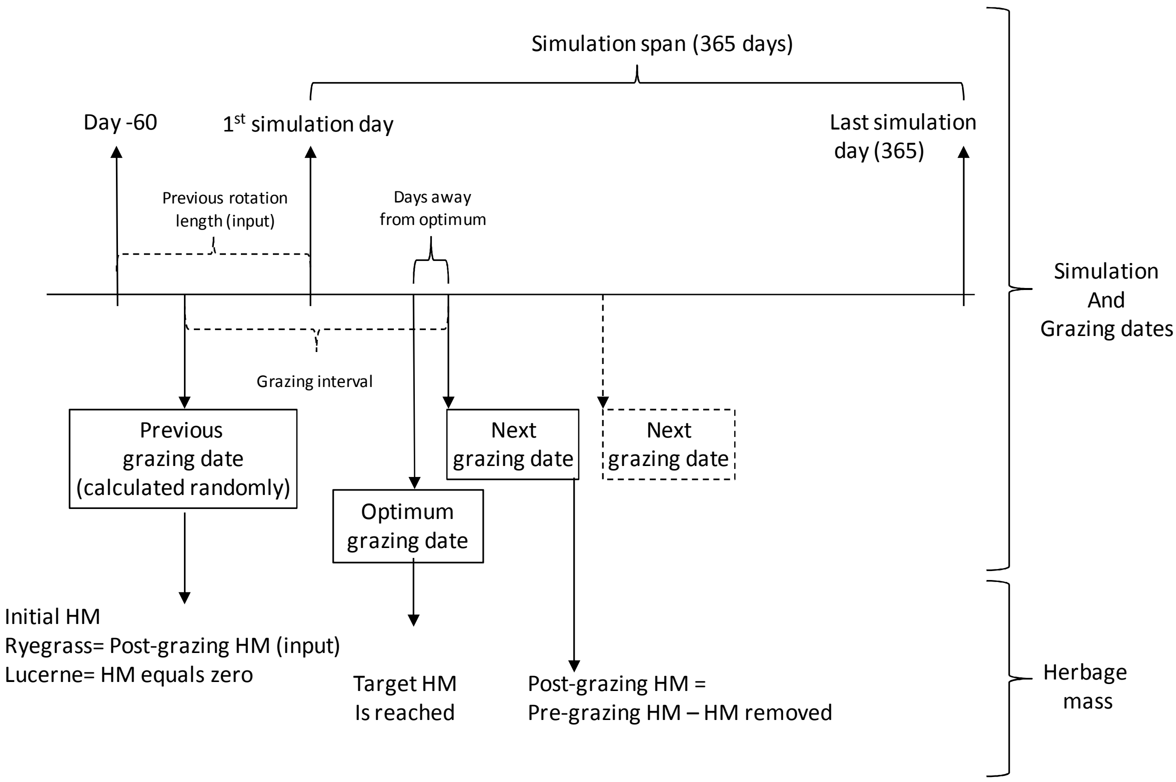

Figure 3 Schematic representation of the simulation of grazing dates and herbage mass (HM) for each paddock within the e-Dairy model.

Pasture budget

An original approach is used to define the order and date in which paddocks are used. The objective is to automate the process, while still representing what happens in reality, giving the user the opportunity to define a policy to use paddocks before the simulation start.

The automation of paddocks is performed by a sub-routine named ‘pasture budget’ (Figure 4), which runs for a period defined by the user as input, named ‘pasture budget frequency’ (Figure 1b, ‘management’). The pasture budget represents what happens in real life, when a ‘pasture walk’ or a ‘consultant visit’ is performed periodically to define the use of paddocks for a future period of time. The pasture budget is a process of internal calculation within the model, for which the user only need to set inputs shown in Figure 1a and 1b.

The pasture budget in e-Dairy consists of a calculation of future pasture offer (expected pasture offer) and future pasture demand (planned allowance) in the whole farm. The ‘expected pasture offer’ is calculated as the sum of the product between pre-grazing HM in each paddock at the calculated ‘optimum grazing date’ and the area of each paddock (Figure 4).

The ‘planned allowance’ is calculated as the target pasture allowance per cow times the number of cows times the number of days in the period to be budgeted (‘pasture budget frequency’) (Figure 4). The target pasture allowance is an input defined with one value per month for each herd, *i.e.*, lactating cows and dry cows (see ‘management’ screen in Figure 1b). Once the planned pasture allowance and the expected pasture offer for the period have been calculated, the following criteria are followed:

If the planned pasture allowance is greater than the expected pasture offer, then ‘make hay or silage’ until planned allowance is less than ‘expected pasture offer’ in the pasture budget period. Make hay or silage is a management sub-routine described in the management section below. Conversely, if the ‘planned pasture allowance’ is less than the ‘expected pasture on offer’ (Figure 4), then the allowance is recalculated, i.e., not enough pasture is available, target pasture allowance cannot be met. Consequently, rotation length will be automatically shortened. In this case, cows will graze down to the target post-grazing set as input and therefore, intake may be restricted, thus, representing what happens at grazing. If paddocks are used in advance to their optimum grazing date, a dialogue box will appear to allow for extra supplementation (see ‘virtual grazing’ section below).

As shown in Figure 4, when not enough pasture is available, the 'planned pasture allowance' per cow is reduced, by multiplying it by the 'ratio offer/allowance', which expresses the proportion of 'planned pasture allowance' that can be met by the 'expected pasture offer'.

Thus, the pasture budget sub-routine matches in advance, approximately, the amount of pasture available with the amount of pasture required. The inputs related to pasture budget sub-routine are: 'pasture budget frequency', 'target pasture allowance' , 'target pre-grazing HM', the number of lactating and dry cows in each period, which is derived from 'calving pattern', as explained below.

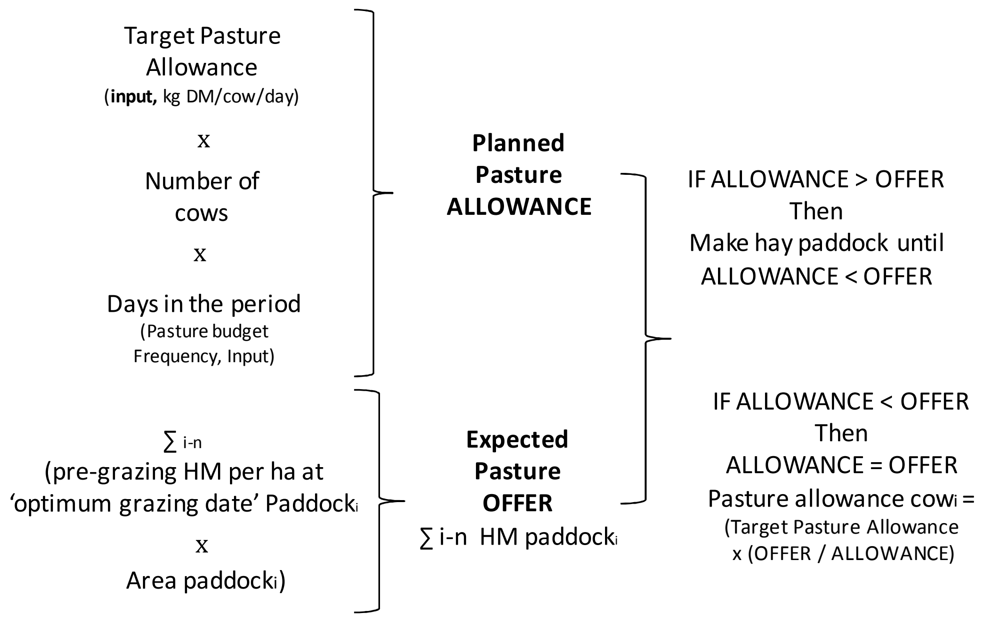

Figure 4 Schematic representation of pasture budget performed for each paddock in the e-Dairy model.

Virtual grazing

Paddocks are virtually grazed, starting with paddocks available on the first day of simulation, *i.e.*, paddocks for which 'optimum grazing date' is the 1st day of simulation or before. The duration of the grazing event, 'grazing time', in each paddock is calculated with the following Equation:

$$\text{Grazing time(days)} = \frac{Pre\text{-}grazing\ HM\ x\ paddock\ area}{Total\ allowance\ per\ day} \qquad (5)$$

where ‘total allowance per day’ is calculated as the summed allowance for all cows. If the ‘grazing time’ of a paddock is less than one day, then, the next paddock available is virtually grazed the same day, and so on. If the ‘grazing time’ of a paddock is more than one day, then, the residual of the day will be available for the next day.

If more than one paddock are available on the same day, then, paddocks not selected will be kept available for grazing for a number of days, which is defined with an input called ‘make hay or silage if days away from optimum is greater than’. If no paddock is available in the day of simulation, the paddock with the ‘optimum grazing date’ closest to the day of simulation will be used prematurely and therefore, the pre-grazing HM of this paddock will not reached the ‘target pre-grazing HM’.

When paddocks are used in advance for a number of days greater than a pre set input named ‘ask if paddock used in advance more than (days)’, a dialogue box appears while simulating and gives the opportunity for inclusion of extra supplements, to reduce the anticipated use of pasture. This extra supplementation will be maintained until the last day of the ‘pasture budget’ period.

The post-grazing HM is calculated as the difference between ‘pre-grazing HM’ and ‘pasture removed at grazing’, the latter being calculated as the sum of daily herbage DM intake of all cows.

Supplements

There is an input table to define the use of supplements, with the following columns: herd, supplement type (concentrates, silage summer crop, silage winter crop, pasture silage, hay summer crop, hay winter crop and pasture hay), starting date, finishing date, kg DM/cow/day offered and efficiency of use, *i.e.*, proportion of the offered supplement consumed. The user can define as many rows, *i.e.*, feeding periods per type of supplement, as desired.

Feed quality

The quality of each feed is defined as input, by its metabolisable energy content (ME; MJ/kg DM) and its neutral detergent fibre content (NDF; % DM). There is an input table for feed quality with a monthly value for ME and NDF for the pasture and for each of the supplements used (Figure 1, tab 'pastures', option 'quality'). The 'pasture quality' set in the input table is affected when the paddock is not used on its 'optimum grazing date', *i.e.*, used in advance or after the 'optimum grazing date'. Pasture quality will decrease (ME decrease and NDF increase) if 'next grazing date' occurs after 'optimum grazing date', and vice versa (Figure 3). The rate at which pasture quality increases or decreases is an input (Figure 1a, 'pastures'), and is defined as a percentage of the value for ME or NDF defined in the input table.

Management

Calving pattern

The e-Dairy model is particularly versatile in terms of calving pattern alternatives. An input table is used to define the percentage of cows calving per week of the year. Then, a calving date is given randomly to each cow, based on a flat probability function. Thus, a seasonal (any season), split calving or an all-year-round calving pattern can be defined.

Dry-off policy

Lactation can be stopped at any stage by setting a dry-off policy, *i.e.*, termination of lactation, based on inputs threshold values for either BCS or milk yield or the number of days until the cow calves again. When any of this threshold values is achieved, the lactation will be finished (see 'dry-off policy' option in 'management' screen, Figure 1b). This policy is applied individually for each cow. The BCS at calving can be set using either the United States, Australian or New Zealand system, with conversions between systems calculated according to Roche *et al*. (2009).

Pregnancy rate and replacement rate

Either all year-round or seasonal calving systems can be selected in the ‘cows’ screen (Figure 1b). For all year-round systems, each cow is randomly allocated a mating date (days after calving), after a voluntary waiting period defined in the input “start of mating” (Figure 1b, ‘cows’). If seasonal system is selected, the “start of mating” set as input is used as a date (days of simulation) after which cows are randomly assumed to be in oestrous and inseminated. For both calving systems, the probability of pregnancy at each service is defined as an input, and a flat probability function is used to randomly decide whether each cow gets pregnant or not, according to the probability of pregnancy set as input for each service. At the current stage of development, the e-Dairy model does not relate pregnancy rate to BCS, but it could be linked in future work, by associating probabilities of pregnancy to levels of BCS.

The number of cows to be replaced by heifers is defined as a percentage of the total number of cows, as a single input (Figure 1b, ‘cows’). In future work, a policy for replacement rate can be implemented, based on age and performance of cows.

Make hay or silage

Make hay or silage is a management sub-routine. There are two situations in which a paddock is allocated to hay or silage. The first situation can occur at the time of pasture budgeting. As explained above, if the expected pasture on offer for the period is greater than the planned allowance, whole paddocks will be used for hay or silage, until the pasture allowance is less than pasture on offer (Figure 4). In this case, the paddock will be used for hay or silage at its calculated ‘optimum grazing date’.

The second situation is when a paddock that was allocated to grazing, at the pasture budgeting time, is not used by its ‘optimum grazing date’. In this case the paddock remains available for grazing for a number of days, which is an input named ‘make hay or silage if days away from optimum is greater than’ (Figure 1b, ‘management’). Once the ‘days away from optimum’ reaches the threshold value, the whole paddock is used to make hay or silage. The percentage of the pre-grazing HM of pasture harvested as hay or silage is defined as input. Additionally, an input table is available to define any month of the year in which hay or silage will not be made.

Economic

An input screen for economic data is available (Figure 1c, 'economics'). It allows the use of two different payment systems, namely price per litre of milk and multiple component price system (kilograms of fat x A + kilograms of protein x B – litres of milk x C), where A, B and C are the values per kilogram of fat and protein and litre of milk, respectively, as it is used in New Zealand and Ireland.

The economic input screen has buttons for access to six input tables, namely: farm incomes, animal expenses, feed expenses, adjustments, overheads (includes depreciation) and assets. Items included in each section are based on DairyNZ (2009) and detailed on Appendix 5. This allows the calculation of two outputs: Operating Profit [Farm incomes – (Animal expenses + Feed expenses + Adjustments + overheads)] and Return on Assets (Economic Farm Profit ÷ Assets × 100).

Simulation

Several simulation options are available in e-Dairy. The simulation screen has two tabs: one for deterministic and another for stochastic simulation (Figure 1c, 'simulation'). The tab for stochastic simulation allows multiple runs, which could represent either different farms in one year or different years for the same farm. Either all or some of the following parameters can be allowed to behave stochastically: genetic merit of cows, pasture production, milk price and supplement price. The probability functions available for each parameter are normal, gamma and flat.

If the aim is to simulate different farms in the same year, genetic merit of the cows must be re-randomised for every run to represent a different farm. If the aim is to simulate different years for the same farm, the genetic merit of cows should be kept constant.

Outputs

Through the 'outputs' screen (Figure 1c, 'outputs'), an output table with a summary of annual performance of the system can be accessed by clicking the button 'farm summary'. Additionally, daily data can be plotted by customising a chart, selecting the output variables to be plotted on each axis (Figure 1c, 'outputs'). In addition to the chart a table is shown with the daily values of the selected variable, either for all the cows or for all the paddocks of the farm. This allows the daily evolution of every variable, for individual cows or individual paddocks, to be checked in detail.

Main sub-routines of e-Dairy

Visual Basic programming language was used to create the sub-routines of e-Dairy. As shown in Figure 5, initially inputs are read; then, paddocks are generated as explained in the section 'paddocks, crops and supplements' above. Subsequently, individual cows of the herd are randomly generated as detailed in the 'herd' section above. After this, a group of sub-routines are used to run daily simulation: Sub Get management rules (see 'management' section), Sub Simulate paddocks dynamic (see 'herbage mass, herbage accumulation, and grazing dates' and 'virtual grazing' sections), Sub Simulate herd dynamic (see 'herd' section) and Sub Run Animal Model (see 'cow module' section).

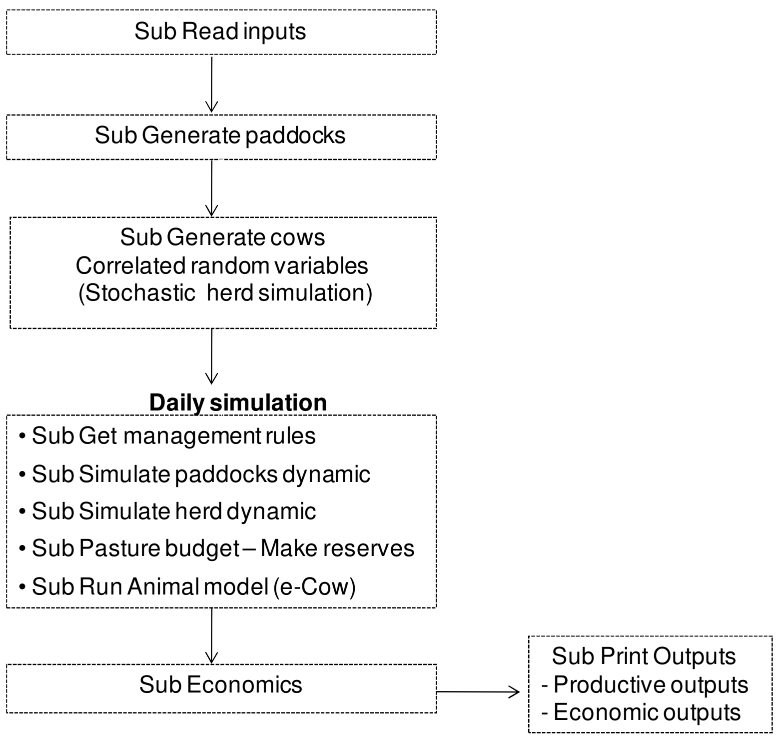

Figure 5 Schematic representation of the main sub-routines in the e-Dairy model.

Model validation

Two independent datasets resulting from stocking rate experiments and not used in the development of the model were used to validate e-Dairy. One dataset was obtained from a farmlet trial comparing five levels of stocking from 2.2 to 4.3 cows/ha of Holstein-Friesian cows, winter-spring calving, grazing on ryegrass-based pastures (offered 0.19 t DM supplement per cow/year) during three years in New Zealand (Macdonald *et al.*, 2008a). The second dataset was obtained from a farmlet trial comparing three levels of stocking rate from 1.6 to 2.6 cows/ha with crossbred Holstein Friesian-Jersey cows (winter-spring calving) grazing on lucerne pastures offered 1.8 t DM supplements per cow/year during two years in Argentina (Baudracco *et al.*, 2011b).

Measured inputs used to validate the model were stocking rate, monthly pasture growth rates, monthly amounts of supplements used per cow, monthly herbage allowances, monthly ME and NDF of pastures and supplements, weekly calving pattern, monthly pre and post-grazing HM, farmlet average for age structure, lactation length, initial BCS and initial LW.

Annual outputs for actual and simulated farmlets were compared, with 21 points for validation in total. Outputs compared were: yields of milk, milkfat and milkprotein (kg/cow/year), BCS and LW at day 365-day of simulation and annual pasture utilisation. The concordance correlation coefficient (Lin, 1989) and the relative prediction error (Fuentes-Pila *et al.*, 2003) were used to evaluate the extent of agreement between actual and predicted values.

The concordance correlation coefficient (CCC) is calculated as: CCC = $\rho \times C_b$, with ρ the Pearson correlation coefficient and C_b the bias correction factor, which is calculated as:

$$C_b = 2\,\sigma_A \sigma_P / (\sigma^2_A + \sigma^2_P + (\mu_A - \mu_P)^2) \quad (6)$$

where σA, μA, σP and μP are the SD and mean of the actual and predicted values, respectively. The Pearson correlation coefficient reflects precision, *i.e.*, degree to which the predicted against actual values cluster about the regression line. The bias correction factor reflects accuracy, *i.e.*, degree to which the regression line adheres to the 45° line through the origin. The Landis and Koch (1977) scale has been used here to describe the degree of concordance, with: 0.21–0.40 being “Fair”; 0.41–0.60 being “Moderate”; 0.61–0.80 being “Substantial”; and 0.81–1.00 being “Almost perfect”.

The relative prediction error (RPE) is defined as the positive square root of the mean square prediction error (MSPE, Equation 7) expressed as a percentage of the mean actual values (µA) (Fuentes-Pila *et al.*, 2003).

$$MSPE = \frac{1}{n}\sum_{i=1}^{n} (Ai - Pi)^2 \quad (7)$$

where P represents the predicted values and A represents the actual observed values for either herbage DM intake, milk yield or LW change. Fuentes-Pila *et al*. (1996) suggested that a RPE value lower than 10% is an indication of satisfactory prediction, whereas a RPE between 10% and 20 % indicates a relatively acceptable prediction, and a RPE greater than 20% indicates poor prediction.

The crossbred Holstein-Jersey cows required to validate the Argentine SR experiment were generated using a Cholesky decomposition (co)variance matrix based on milk yield, LW, and parameters of the Wilmink function defining milk fat and milk protein curves for the Argentine experiment (Appendix 3).

RESULTS

Model validation

The accuracy of prediction of the e-Dairy model is shown in Table 1 and Figure 6, where predicted data was compared with actual data from two farmlets trials in which different levels of stocking rate were explored. One dataset was from a New Zealand trial with ryegrass-based pastures and less than 0.15 t DM/cow/year of imported supplement and the other dataset was from an Argentine trial with lucerne-based pastures and 1.8 t DM/cow/year of imported supplement.

Table 1 Comparison of actual (Macdonald *et al*., 2008a; Baudracco *et al*., 2011b) and predicted (e-Dairy) data for annual pasture utilisation (%, pasture consumed at grazing/pasture production), annual yields of milk, fat and protein (kg/cow), live weight (LW) at calving (kg/cow) and BCS at calving (scale 1-10). The validation dataset comprises data from 21 farmlets.

		Pasture utilisation	Milk yield	Milk solids yield	Live weight	BCS
Actual	Mean	63.8	4 869	384	502	4.5
	NZ	69.0	4101	335	495	4.7
	Arg.	50.9	6788	507	520	3.9
Predicted	Mean	63.5	4 687	362	484	5.0
	NZ	68.5	4095	325	475	5.2
	Arg.	51.9	6168	453	506	4.4
R	Mean	0.93	0.96	0.94	0.84	0.70
	NZ	0.88	0.87	0.89	0.86	0.72
	Arg.	0.92	0.92	0.90	0.78	0.66
RPE	Mean	6.4	8.8	8.5	3.3	10.1
	NZ	5.5	8.7	8.4	3.8	8.4
	Arg.	9.4	3.4	4.1	4.4	11.2
CCC	Mean	0.93	0.93	0.90	0.69	0.48
	NZ	0.87	0.86	0.87	0.77	0.54
	Arg.	0.86	0.61	0.55	0.58	0.41

R = Pearson correlation coefficient, RPE = Relative prediction error, CCC = Concordance correlation coefficient.
NZ = New Zealand, Arg. = Argentina

In validation analysis, combining both datasets, the e-Dairy model showed satisfactory accuracy of prediction, with RPE lower than 10% and with CCC over 0.80 for annual pasture utilisation, yields of milk, fat and protein, and CCC of 0.69 and 0.48 for LW and BCS score at the end of the 365-day period, respectively (Table 1).

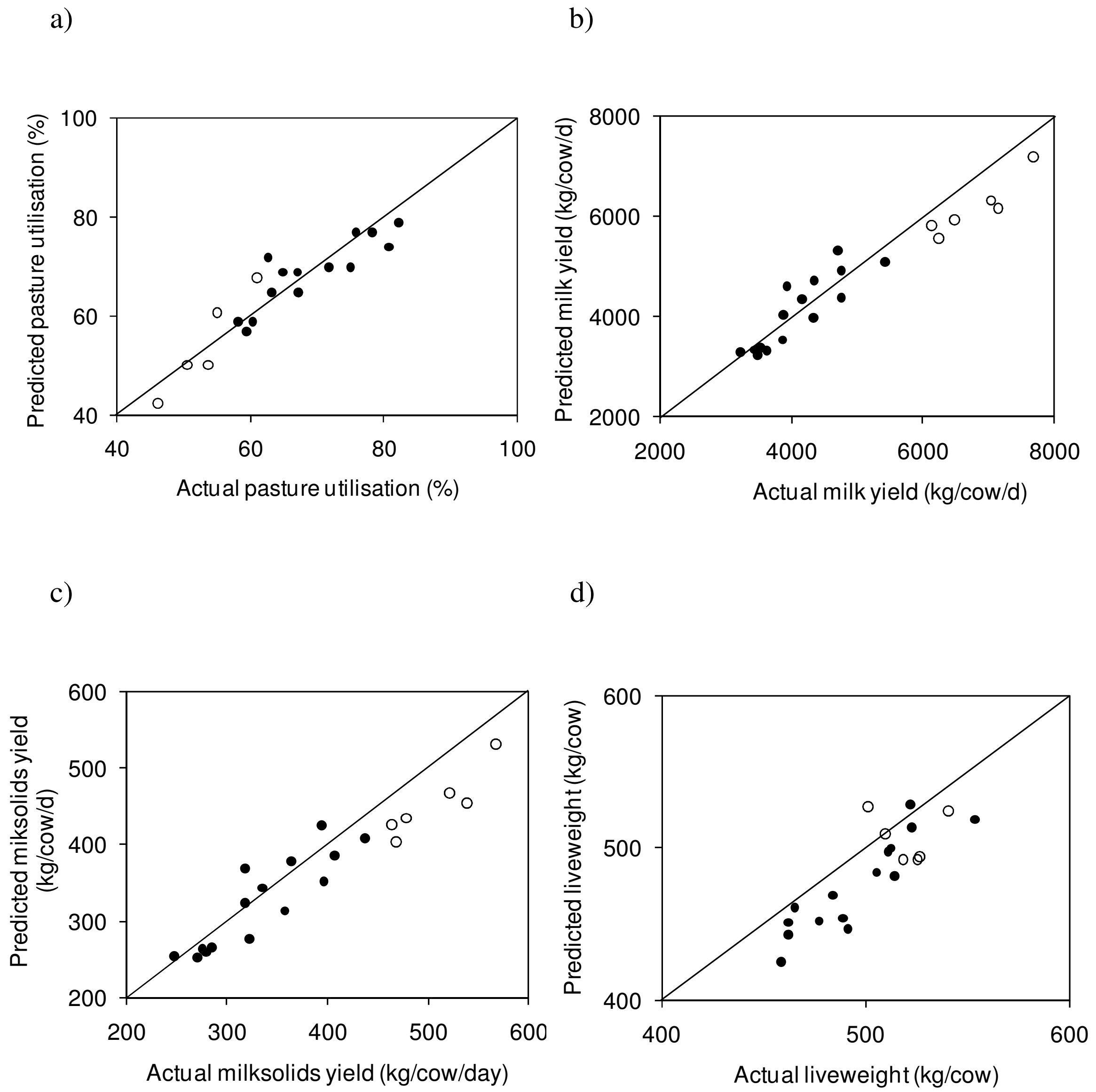

Figure 6 The relationship between predicted and actual values averaged per farmlet for (a) annual pasture utilisation (pasture consumed/pasture grown), (b) annual milk yield (kg/cow/day), (c) annual milksolids yield (kg/cow/day), and (d) LW (kg/cow/day) at day 365-day of simulation. Actual values obtained from two farmlet system trials: one evaluating 5 farmlets over 3 years using ryegrass-based pastures (●) (Macdonald *et al.*, 2008) and the other evaluating 3 farmlets over 2 years using lucerne-based pastures (○) (Baudracco *et al.*, 2011b).

The model under predicted annual pasture utilisation (-0.5%), milk yield (-182 kg/cow/year), milk fat yield (-14 kg/cow/year), milk protein yield (-9 kg/cow/year) LW (-18 kg/cow) and over predicted BCS (+0.5, scale 1-10) at the end of the 365-day period (Table 1). The accuracy of prediction was higher for the New Zealand dataset than that of the Argentine dataset (Figure 6 and Table 1).

Model simulations

As an example of the practical applications of the e-Dairy model, a stochastic simulation (n=250) was performed for an average New Zealand dairy farm owner operated. Physical data for the average farm were obtained from Livestock Improvement Corporation (2010) and average costs were obtained from DairyNZ (2010), see Appendix 5. The farm was simulated for 360 cows New Zealand HF, average LW of 477 kg in 128 effective hectares (2.8 cows/ha), with a start calving date on 20 July and with 150 kg DM of imported supplement per cow/year.

Pasture dry matter produced on-farm was set to behave stochastically in the simulation, using a normal distribution with a mean of 13.5 ± 1.25 t DM/ha/year and milk payout per kg MS was also set to behave stochastically, using a normal distribution with a mean of $NZ 5.3/kg MS, while all other inputs were held constant. A dry-off policy was implemented so that cows were dried-off individually at 280 days in milk if milk yield was less than 8 kg/cow/day or at 250 days in milk if BCS was less than 4 in the New Zealand scale, 1-10. As an average of the 250 simulations of the same farm, MS yields were 329 kg per cow and 925 kg per hectare.

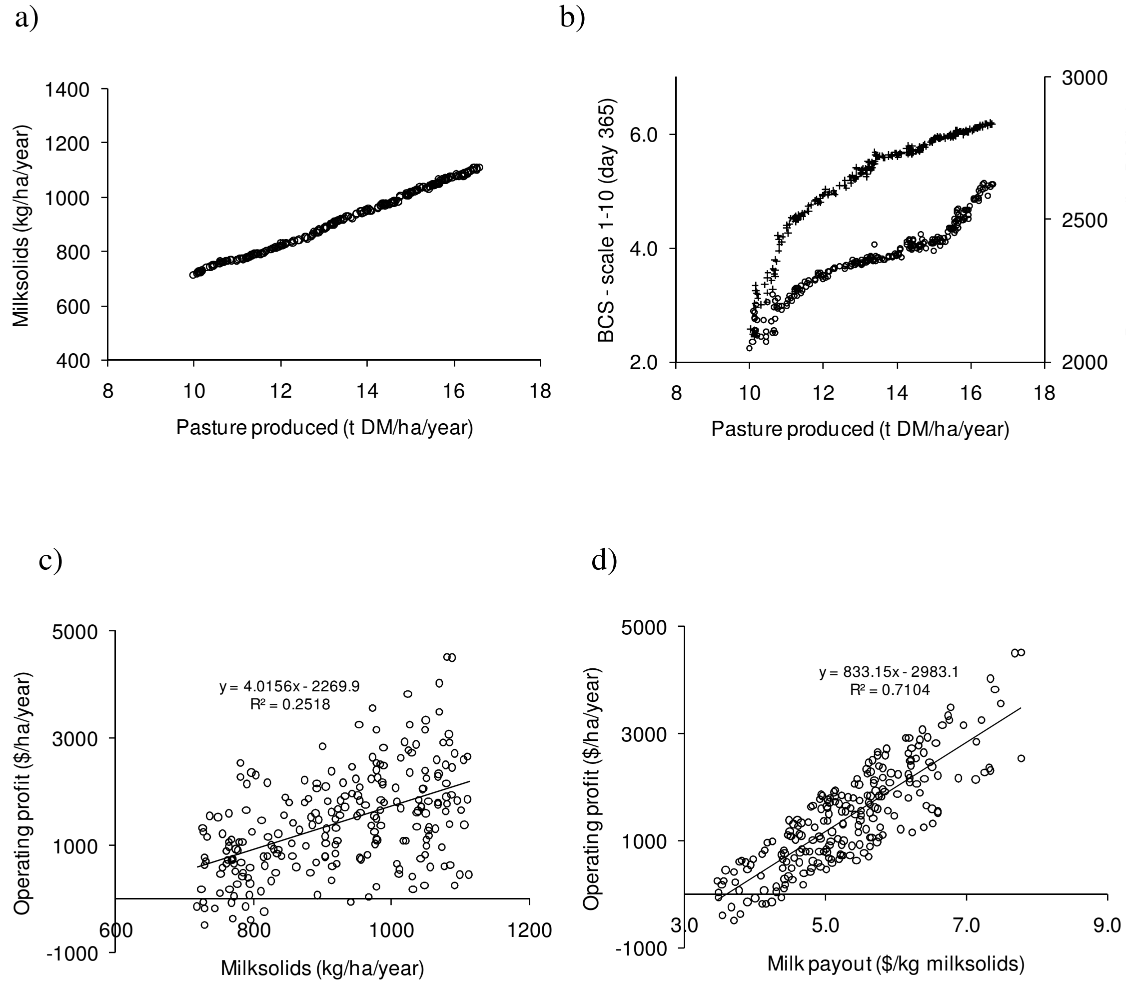

Figure 7 Stochastic simulations (n=250) performed with e-Dairy, for physical and economic performance of a typical pasture-based dairy farm in New Zealand with 360 cows on 128 ha and with 0.15 t DM imported supplement/cow/year. (a) Annual milksolids production and (b) body condition score (+, upper) and pasture cover (○, lower) at day 365-day of simulation as a function of pasture produced. Operating profit as a function of milksolids production per hectare (c) and as a function of milk payout (d). Pasture grown and milk payout were set to behave stochastically, with all other variables held constant.

Results of this stochastic simulation are shown in Figure 7. Examples of physical outputs are shown in Figure 7a and 7b, while examples of economic outputs are shown in Figures 7c and 7d. Yields of MS/ha, BCS (scale 1-10) and pasture cover (HM, kg

DM/ha) at day 365-day of simulation increased as pasture production increased (Figure 7a and 7b). Operating profit ($/ha/year) increased as a result of higher MS production resulting from higher randomised pasture production, but a big dispersion (R^2=0.25) of results can be observed (Figure 7c), as the milk price was also randomly allocated for each simulation. This is confirmed by comparing Figure 7c and 7d, from which it is observed a stronger dependence of operating profit on milk price (R^2=0.71) than on milksolids produced per hectare.

DISCUSSION

The e-Dairy model was designed to predict the physical and economic performance of milk production systems and to explore the interactions between genetic merit, supplementation, stocking rate and market prices for systems using either ryegrass-based or lucerne-based pastures. It simulates each individual cow and each individual paddock, on a daily basis for a 365-day period, and allows stochastic behaviour for key variables such as genetic merit, pasture growth, milk price and supplement prices. Simulations can be performed using any calving pattern, imported supplements, summer and winter crops.

The majority of whole-farm models for grazing dairy systems are restricted to specific conditions, such as the type of cows and the type of pasture used in a particular region of the world. The e-Dairy model is relatively versatile in these respects, since it includes equations to predict herbage DM intake from both ryegrass-based and lucerne-based pastures, and for allowance expressed at different cutting heights, as is commonly done in different countries. In addition, the genetic merit of the cow is defined by several factors including her potential milk, fat and protein yield, LW and other parameters (Baudracco *et al.*, 2011a). However, at the current stage of development, only three types of cows can be randomly generated, namely two strains of HF, New Zealand and North American (Macdonald *et al.*, 2008b) and crossbreed Holstein-Jersey cows (described in Baudracco *et al.*, 2011b).

Management strategies can be implemented in the e-Dairy model through decision rules expressed in the form of “if condition then action”. Examples of these decision rules are the grazing management options, the hay making policy and the cow dry-off policy, all explained in the methodology section. Such rule-based representations of farm management have shown promise when included in farm system modelling (Woodward *et al*., 2008).

Model validation

In validation tests (Table 1), using the measured annual outputs of experimental farmlets, the model predicted with a high degree of accuracy (CCC>0.80 and RPE<10%) for annual pasture utilisation, and per farmlet annual yields of milk, milkfat and milkprotein. However, the accuracy of prediction was only moderate for LW and BCS, when considering the CCC (Table 1).

Overall, these levels of accuracy are similar or higher than those reported for similar whole-farm models for grazing dairy systems such as Farmax Dairy Pro (Bryant *et al.*, 2010) and WFM (Beukes *et al.*, 2008). However, it is important to note that in the e-Dairy model, pasture growth rate is not predicted but is considered as an input, which reduces the prediction error, while in WFM, not only milk yield is predicted but also pasture growth rate.

The bias of prediction, reflected by the values of the CCC, for milk yield and MS yields were higher for the Argentine dataset (lower CCC) than for the NZ dataset (Table 1). This is possibly due to the potential yields of milk and potential MS yield used to test the Argentine dataset, which may have caused under-predictions of milk and MS yields.

Model simulations

The stochastic simulation performed for an average New Zealand dairy farm (Figure 7) shows the ability of the model to predict physical and economic performance of dairy systems facing uncertainty, in this case, for pasture grown and milk price, with all other inputs held constant.

Physical outputs resulting from the stochastic simulation, such as MS yield per hectare, BCS and pasture cover at day 365-day of simulation show minimal variation for the same level of pasture grown in the farm (Figures 7a and 7b). This is due to the fact that the genetic merit of the herd was set to behave deterministically, and therefore, the same herd was used for each simulation, and consequently, as pasture grown increased, MS yield, BCS and pasture cover increased. Figure 7a shows the MS response to extra pasture grown.

The situation is different for the economic outputs of the same simulation (Figure 7c). In this case, for the same level of MS yield the operating profit ($/ha/year) showed greater variation; due to the fact that simulations with similar MS/ha/year were randomly allocated different milk prices. By comparing Figures 7c and 7d the stronger dependence of operating profit on milk price than on MS produced per hectare is apparent. Overall, Figure 7 shows that pasture produced on farm and milk payout are two of the most important drivers of profitability in the pasture-based dairy systems of New Zealand.

Further analysis could be done for dairy systems which import more supplements, by setting not only pasture grown and milk price to behave stochastically, but also supplement price, and comparing the relative weight of both supplement price and milk price on operating profit.

The e-Dairy model can simulate different farms by setting genetic merit to behave stochastically across farms, which will result in the generation of herds with differing genetic merit, and this when combined with stochastic behaviour of pasture grown can represent two of the most important features for a group of pasture-based dairy farms.

Model limitations and potential

The e-Dairy model does not link BCS to reproduction, and does not include health issues. However, the effects of BCS on reproduction could be implemented in future work by relating BCS levels to the probabilities of pregnancy, which are already calculated in the e-Dairy model (see Figure 1b, reproductive performance in the 'cows' screen). Likewise, the effect of health problems on the performance of cows could be implemented with a probabilistic approach supported by experimental data for the main health problems of dairy herds, such us mastitis and lameness.

At the current stage of development, the e-Dairy model is based only on ME. This approach was used based on the fact that the amount and quality of protein in temperate pastures, combined with its high digestibility and rapid rate of passage through the digestive tract, ensures that metabolisable protein supply does not usually limit milk production (Holmes & Roche, 2007). However, there may be excess protein in leafy spring and especially autumn pastures with an associated energy cost in excreting the excess protein, or lack of adequate protein in diets with high proportion of maize silage. In this kind of cases the inclusion of a protein balance would improve predictions.

Climatic effects are not accounted for at the current stage of development of the e-Dairy model. In many temperate regions, heat stress can have detrimental effects on milk yield (Kendall *et al.*, 2006) and reproductive performance of dairy cows (De Rensis & Scaramuzzi, 2003). Experimental data reporting a wide range of results of the effect of heat stress on cows of differing levels of milk yield may provide the parameters required to include this effect in the model.

Prediction of milk yield depends on parameters that shape the potential milk yield and the target BCS curve (see Cow module section above). Parameters for HF cows of North American and New Zealand genetics are included in the model for both potential milk yield and target BCS curves. However, for cows of different genetic background, such as Jersey cows, parameters for potential milk yield and target BCS curves will need to be calculated from experimental datasets.

Even though pasture utilisation was accurately predicted in the validation tests of this study, the fate of pasture not utilised at grazing, *i.e.*, wasted or used to make silage or hay, was not validated. The automatic procedure implemented in the model to make hay or silage from pastures may over estimate the amount of hay or silage made to the detriment of the estimated amount of pasture wasted, since in real farms it is not realistic to think that hay or silage would be made in each paddock exactly after "certain amount of days away" from "optimum grazing date", as occurs in the model.

The ability to account for stochasticity makes the model robust in the face of uncertainty. This characteristic allows further analysis of risk, and particularly the evaluation of the trade-offs between profit and risk (Woodward *et al.*, 2008).

Two important features of the e-Dairy model are its ability to randomly generate individual cows with internally correlated variables and the ability to account for genotype by environment effects, since it includes the e-Cow model (Baudracco *et al.*, 2011a). These two features are the basis for future work on ‘simulated progeny tests’ of bulls under different selection objectives and selection schemes, to explore whether different selection indices can differ in their long term results when applied to different ‘feeding environments’. If this is to be implemented, the model will need to run consecutively for several years (currently simulating only a 365-day period) and a sire selection and allocation module will need to be included.

The model currently simulates the performance of each cow in response to the simulated feeding environment, therefore, a selection module could be implemented to select cows to be culled based on a selection index, after every simulation, thus allowing a genetic improvement program to be implemented.

CONCLUSIONS

This model is unique in its ability to simulate pasture-based dairy farms, since it accounts simultaneously for stochasticity in individual cows, individual paddocks and in the whole-farm, for some of the key variables of dairy system such as pasture grown, genetic merit of cows, milk price and supplement price. The animal model (e-Cow) included in the e-Dairy model was proven to be able to simulate annual performance of dairy cows with acceptable levels of accuracy for both ryegrass-based and lucerne-based dairy systems.

The e-Dairy model can be used to explore the effects and interactions of feeding level and genetic merit of cows, for grazing dairy systems with differing calving patterns, evaluating the trade-offs between profit and the associated risk. The model has the capacity with further development to simulate progeny tests and evaluate the impact of using different genetic breeding indexes.

ACKNOWLEDGEMENTS

The authors thank Marcelo Zamateo for his support in the development of this model.

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Chapter 8

General discussion

OVERVIEW

This thesis focused on the effects of feeding level and genetic merit of the cow, and their interactions, on the efficiency of pasture-based dairy systems through field and modelling studies. A dynamic and stochastic whole-farm model was developed to predict physical and economic performance of pasture-based dairy systems to explore interactions between genetic merit, feeding level (stocking rate and supplementation) and market prices for systems using either ryegrass-based or lucerne-based pastures. A crucial aspect of this research was to produce a versatile model. In this context, the term versatile model means a model that is able to simulate grazing dairy systems not restricted to a particular type of pasture, to a particular type of cow or to a particular calving pattern thus, a model that can be used beyond the limits of the dairy systems in one particular country.

The effects of, and the interactions between, stocking rate (SR), supplementation and genetic merit on grazing dairy systems were reviewed in Chapter 2 for ryegrass-based dairy systems. The effects of stocking rate (SR) on lucerne-based dairy systems were reviewed and tested with a 2-year farmlet experiment reported in Chapter 3 and with a short-term experiment reported in Chapter 4, the latter focusing on intake of individual cows. Chapters 5, 6 and 7 focused on the development of a whole-farm model; with Chapter 5 reporting on the development and validation of an intake model for ryegrass-based pastures; Chapter 6 reporting on the development and validation of an animal model that predicts herbage intake (HI), milk yield and live weight change in dairy cows grazing temperate pastures, with and without supplementary feeding; and Chapter 7 describing and validating a dynamic, stochastic, whole-farm model that predicts physical and economic performance of grazing dairy systems. Both the animal model (Chapter 6) and the whole-farm model (Chapter 7) can be used for either ryegrass-based or lucerne-based pastures.

Versatility for the type of pasture was obtained by developing different equations to allow the model to predict herbage intake (HI) for ryegrass-based pasture when herbage allowance (HA) is expressed at ground level (Chapter 5), for ryegrass-based pastures with herbage allowance (HA) expressed 4 cm above ground level (using equations derived from data reviewed in Chapter 2), and for lucerne-based pasture when HA expressed 4 cm above ground level (Baudracco *et al*., 2006).

Versatility for the type of cow was obtained by defining the genetic merit of the cow by her potential total yields of milk, fat and protein, LW and parameters related to genetic targets for BCS at different stages of the reproductive cycle (e-Cow model, Chapter 6).

The whole-farm model was validated for ryegrass-based dairy systems using existing data from a 3-year farmlet experiment in New Zealand (NZ) (Macdonald *et al.*, 2008) comparing five levels of SR (2.2 to 4.3 cows/ha). In this experiment, Holstein-Friesian cows with winter-spring calving, grazing on ryegrass-based pastures and offered 0.15 t dry matter (DM) supplement per cow/year were evaluated. The validation of the model for lucerne-based dairy systems was performed with data from a farmlet experiment carried out in Argentina, designed and completed as part of the current thesis (Chapter 3). This experiment compared three levels of SR (from 1.6 to 2.6 cows/ha) over 2 years for cows grazing on lucerne-based pastures and offered 1.8 t DM supplements/cow/year (Baudracco *et al.*, 2011).

MAIN CONTRIBUTIONS OF REVIEW CHAPTER

Relative energy deficit

A main conclusion from the review chapter is that milk response to supplements depends mainly on the size of the relative energy deficit, which is the difference between the potential energy demand and actual energy supply. The concept of “relative energy deficit” was first introduced by Penno *et al.* (2001) and further explored by Holmes & Roche (2007). The review chapter shows how all the known factors affecting milk response to supplements impact on the relative energy deficit, either affecting demand for energy within the cow or energy supplied.

The theoretical basis supporting the concept of relative energy deficit as the main driver of the milk response to supplements is robust; however, quantitative demonstration of this theory will contribute to further understanding of the effect of the factors affecting the milk response to supplements. Previously, Penno *et al.* (2001), using multiple regression analysis, quantified the relative energy deficit as the reduction in milksolids (MS) yield that occurred as restricted HA treatments were imposed on cows. However, this measure of relative energy deficit has limited applicability for conditions other than those from which the relationships were obtained, *i.e.*, genetic merit of cows, quality of pasture and quality of supplements.

An improved, original and broader approach to quantify the relative energy deficit of cows can be developed on the basis of the work completed in the current thesis, as follows:

$$\text{Relative energy deficit} = \text{Potential energy demand} - \text{Actual energy intake}$$

With the potential energy demand being:

$$\text{Potential energy demand} = MEm + MEp + MEgr + MEmilk + ME\ from/to\ BCS\ change$$

where *MEm* is the ME for maintenance, *MEp* is the ME for pregnancy, *MEgr* is the ME for growth in the case of young animals; *MEmilk* is the ME required for milk synthesis and *ME from/to BCS change* is the ME mobilised or synthesised from/to body lipid reserves. Requirements for *MEmilk* and *ME from/to BCS change* can be calculated as proposed by Vetharaniam *et al*. (2003) and Friggens *et al*. (2004), respectively, and further developed in the e-Cow model (Chapter 6). This method of quantification of the relative energy deficit can be tested in future research with experimental data reporting the milk response to supplements by cows of different genetic merit, offered differing levels of supplementation.

Relationship between herbage allowance and herbage intake

Previous studies reviewed the relationship between HA and HI. However, many reviewers combined the results from experiments measuring HA at ground level with the results from studies reporting HA at a cutting height of about 4 cm. In the review chapter of this thesis, a clear distinction was made between experiments expressing HA at ground level or above a cutting height, and the relationship between HA and HI was quantified by performing a meta-analysis based on the results of 31 studies carried out in grazing conditions with perennial ryegrass dominant pastures. It emerged from the meta-analysis performed that HA for maximum HI was 78.4 and 30.9 kg DM/day when HA is expressed at ground level and 4 cm above ground level, respectively.

Differences between Holstein-Friesian strains

The review completed in this thesis bring together results from experiments comparing the performance of Holstein-Friesian (HF) strains in New Zealand, Ireland and Australia under grazing dairy systems importing supplements (0.3 to 1.7 t DM/cow/year). By integrating results from 13 treatments in those experiments, it was found that as the proportion of North American (NA) genetics increased from 20% to 80%, milk response to supplements increased by 0.3 kg milk/kg supplement consumed (R^2=0.70) and pregnancy rate decreased by 13% (R^2=0.44).

MAIN CONTRIBUTIONS OF EXPERIMENTAL CHAPTERS

A farmlet study was conducted as part of this thesis to compare the production, quality, persistence and utilisation of pastures, milk production and reproduction for crossbred Holstein-Jersey dairy cows stocked at three different SR over two years, grazing on lucerne pastures. This appears to be the first field whole-farm study exploring the relationships between SR, grazing efficiency and milk production on lucerne-based dairy systems. Within the farmlet experiment, a short-term experiment was carried out to evaluate the effects of HA on individual HI, milk yield and grazing behaviour of supplemented dairy cows grazing lucerne-based pastures in early lactation, and to compare two methods to estimate individual HI: the animal performance method and the LIPE® method.

Comparison of ryegrass-based and lucerne-based dairy systems

The discussion on similarities and differences between ryegrass-based and lucerne-based pastures for dairy cows, which is included in the two experimental chapters, is an original contribution from this thesis. Pasture production, pasture quality, HI and milk yield reported for ryegrass-based farmlet studies were compare to the findings from this thesis using lucerne-based pastures. For well-managed ryegrass-based pastures, as SR increases pasture production usually increases, because periodic defoliation and relatively low residuals are required to renew photosynthetic efficiency. In contrast, re-growth of lucerne-based pastures is almost independent of residual leaf, since the energy used for re-growth comes from reserve carbohydrates in the crown and roots, and this depends on frequency of grazing. This explains why in the experiment reported in Chapter 3, different grazing residuals arising from different SR did not affect pasture production, in contrast to the findings reported for ryegrass-based pastures. It must also be considered that mechanical cutting of pasture residuals to 5 cm was completed after every grazing in the experiment reported in Chapter 3, which removed effects of SR on quality of the pasture on offer at the next grazing.

Effects of SR on herbage intake and milk yield

The effects of SR on milk yield per cow have been equivocal. However, common factors explaining inconsistent results have been identified in this thesis. Thus, feed intake at different stages of lactation and the use of supplementary feed have been found to consistently account for differences in effects of SR on milk yield per cow. For all studies in which SR had no effect on milk yield per cow, including the experiment reported in Chapter 3, feed restrictions imposed by high SR were somehow prevented, either by supplementation (Fales *et al.*, 1995) or by delaying calving date (Dillon *et al.*, 1995). In contrast, when feed restrictions in early lactation were evident, with minimum supplements permitted, SR had a significant effect on herbage intake and milk yield per cow (Macdonald *et al.*, 2008).

Quantification of the effects of SR and supplements on lucerne-based dairy systems

An increase in SR of 1 cow/ha together with an increase of 1.8 t DM/ha/year of imported supplements, tested in the experiment reported in Chapter 3, resulted in an increase of 2.4 t DM/ha/year of pasture consumed ($P<0.05$), and 5,840 kg milk/ha/year of milk yield ($P<0.05$).

Validation of an intake marker (LIPE®)

An external intake marker developed from a purified enriched lignin (LIPE®) had been proven to be a reliable estimator of faecal output for several animal species and therefore, has the potential to be used to estimate HI at grazing. However, its accuracy to estimate HI of dairy cows at grazing has not yet been published in an international journal. Chapter 4 reports on a short-term experiment that compares the LIPE® method with the animal performance method to estimate HI. The animal performance method is based on the metabolisable energy requirements for lactation, live weight (LW) change, maintenance of the cows and the metabolisable energy content of the herbage. Results showed that the estimates of HI from the two methods were similar. However, further research is needed to explore the suitability of LIPE® to predict HI for dairy cows at grazing.

Comparison of estimates of herbage intake using LIPE® or the sward cutting technique

The relationship between HA and HI was studied for dairy cows grazing lucerne-based pastures, but always with estimations of intake based on a group of animals, using the DM disappearance in the sward measured by the sward cutting method. The experiment reported in Chapter 4, showed that estimations of HI differed between treatments when using the LIPE® method ($P<0.05$), which is based on estimates of individual intakes, whereas when using the sward cutting method, based on herd average intake, there was no difference. This highlights the importance of using dietary markers to investigate the relationship between HA and HI for cows grazing lucerne-based pastures.

Efficiency of grazing lucerne pastures

The experiment reported in Chapter 4 also showed that high grazing efficiency (870 g/kg; herbage consumed/herbage offered) and high milk yield per cow (29 kg milk/cow/day) are achievable by restricting HA and offering moderate to high amounts of supplements for dairy cows grazing lucerne-based pastures.

MAIN CONTRIBUTIONS OF MODELLING CHAPTERS

Development of a model to predict herbage intake

A model previously developed to predict HI of cows grazing lucerne-based pastures (Baudracco *et al.*, 2006) was adapted to predict daily HI of dairy cows grazing ryegrass-based pastures. The model accounts for ingestive, physical and metabolic limitations of HI at grazing and also accounts for the effects of genetic merit of cows. The model predicts higher HI and lower substitution of pasture by supplements for cows of higher genetic potential for milk yield. When validated, the model successfully predicts pasture DMI of grazing cows under different combinations of feed supply and genetic merit.

Development of an animal model (e-Cow)

The e-Cow model is innovative because it predicts the performance of dairy cows at grazing, combines nutritional and genetic drives to predict energy partitioning within the cow and includes genetic differences between cows in the prediction of both HI and energy partitioning. Few mathematical simulation models address all these challenges simultaneously. In addition, whole-lactation performance is predicted on a daily basis at a single step, whereas most of the animal models for dairy cows at grazing predict animal performance for a single day at a time. An important feature of the e-Cow model is its genotype by environment sensitivity, which comes from the use of unique metabolic limits to intake, unique genetic targets for BCS, and unique parameters for the potential milk yield of each cow, according to her genetic merit.

The main uses of the e-Cow model will be for applied research, teaching and extension purposes. The web-based version of e-Cow could be particularly useful for teaching, allowing a quick and practical understanding of the effects of feeding level on DM intake, milk yield, and changes in BCS and LW of cows of different genetic merit under differing feeding scenarios.

Development of a whole-farm model (e-Dairy)

The novelty of this whole-farm model is its ability to simulate the performance of individual cows on a daily basis, allowing stochasticity for key dairy system variables including the amount of pasture grown, genetic merit of cows and milk and supplement price. In contrast, whole-farm models that account for stochasticity, usually work at a herd level and/or a monthly basis, while whole-farm models for grazing systems simulating individual cows on a daily basis do not account for stochasticity. Another distinctive feature of the e-Dairy model is its versatility to simulate either ryegrass-based or lucerne-based dairy systems with either seasonal or all year-round calving systems for cows of different genetic merits.

At the current stage of development, the main use of the e-Dairy model could be to investigate the effects, and interactions, of genetic merit and feeding level, *i.e.*, supplementation and SR. In addition, the risk associated with different feeding strategies can be explored, based on the stochastic behaviour allowed in the model for key system variables. The e-Dairy model can perform simulation studies not only for a single farm but also for a group of farms, by generating farms with cows of different genetic merit and with different amounts of pasture grown. Thus, the risk associated with management strategies could be evaluated at a global scale, with each farm giving a unique response.

PRACTICAL APPLICATIONS OF THE WHOLE-FARM MODEL (e-Dairy)

The following pages demonstrate the application of the whole-farm model through two examples of stochastic simulations conducted for both ryegrass-based dairy system in NZ and lucerne-based dairy systems in Argentina at two levels of SR. As SR increased, the following expenses were increased in proportion to the number of cows: labour, animal health, breeding and herd testing, farm dairy expenses, electricity, freight, young stock grazing-off and depreciation.

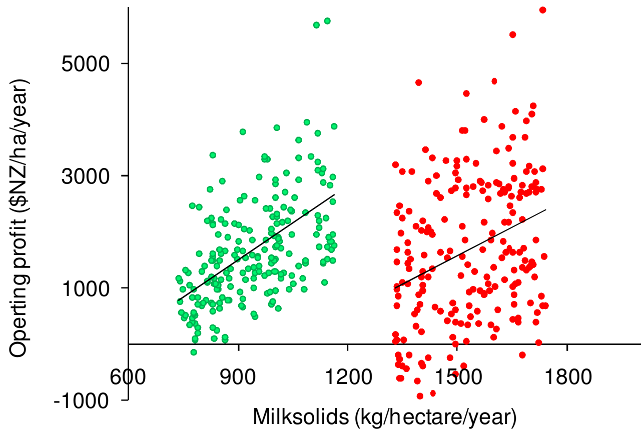
Stochastic simulation for ryegrass-based dairy systems in New Zealand

Owner operated farms were simulated (n=200) for ryegrass-based dairy systems, with average economic data (expenses) based on DairyNZ (2010) and described in Appendix 5. Two types of farms were simulated, one named “low input”, similar to the average NZ dairy farm (Livestock Improvement, 2010), with 360 cows on 128 effective hectares (2.8 cows/ha) and 0.15 t DM/cow/year of imported supplement. The second farm, named “high input” had 448 cows on 128 effective hectares (3.5 cows/ha) and with 1.45 t DM/cow/year of imported supplement. In both cases, NZ HF cows (average LW of 477 kg) were simulated, with calving starting on 20 July (10 weeks calving period), and with pasture DM produced on-farm set to behave stochastically using a normal distribution with a mean of 14 t DM/ha/year. Milk payout per kg MS and imported supplement (12 MJ ME/kg DM) price were also set to behave stochastically using a normal distribution, with means of \$NZ5.5/kg MS (equivalent to \$US4.1/kg MS), and \$NZ0.46/kg DM supplement (equivalent to \$US0.35/kg DM). A dry-off policy was implemented so that cows were dried-off individually at either 280 days in milk if milk yield was less than 0.7 kg MS/cow/day or at 270 days in milk if BCS was less than 4 (NZ scale, 1-10) or at 60 days before next calving. A replacement rate of 20% was assumed.

The performance of each of the systems was stochastically simulated 200 times and the average MS yields per cow were 334 ± 43 and 439 ± 36kg MS/cow for low and higher input farms, respectively. The average MS yield per hectare per year were 941 ± 120 kg MS/ha/year in the low input farm and 1534 ± 127 kg MS/ha/year in the high input farm. However, operating profits were similar, with 1681 ± 1004 and 1703± 1272 \$NZ/ha/year for the low and high input farms, respectively. Even though the average profit per hectare was similar, high input farms showed higher variation in terms of economic profit, showing both the greatest and the lowest values of profit per hectare (Figure 1a), the latter being associated with higher risk. The lack of difference for average operating profit between the simulated low and high input farms supports the findings from a Survey of 626 owner-operated dairy farms in New Zealand (Silva-Villacorta *et al.*, 2005).

Figure 1b shows that at milk prices lower than \$NZ5.5/kg MS (\$US4.1), the lower input systems were more profitable than the higher input systems, while at prices higher than \$NZ5.5/kg MS the opposite occurred in this simulation study. These examples show the potential of the whole-farm model developed in this thesis to explore the combined effects of SR and supplementation on economic outputs for ryegrass-based dairy systems facing uncertainty, in terms of pasture grown, milk price and supplement price.

a)



b)

Figure 1 Stochastic simulations (n=200) performed with e-Dairy for physical and economic performance of ryegrass-based dairy farms owner operated in New Zealand. (●) Low input systems with 2.8 cows/ha and 0.15 t DM/cow/year of imported supplement and for (●) high input systems with 3.5 cows/ha and 1.5 t DM/cow/year of imported supplement. Pasture grown (mean 14 t DM/ha/year), milk payout (mean $NZ5.5/kg MS) and supplements price (mean $NZ0.46/kg DM) were allowed to behave stochastically using a normal distribution, while all other variables were held constant. The average MS were 941 ± 120 kg MS/ha/year in the low input farm and 1534 ± 127 kg MS/ha/year in the high input farm. Average operating profits were 1681 ± 1004 and 1703± 1272 $NZ/ha/year for the low and high input farms, respectively.

Stochastic simulation for lucerne-based dairy systems in Argentina

For the stochastic simulation of lucerne-based dairy systems (n=200), farms on leased land were simulated ($US540/ha/year of leasing costs), with 12% of milk income used to pay for labour. The two farms were simulated to represent the low and high SR farmlets of the experiment reported in Chapter 3.

Average economic data (expenses) were based on Margenes Agropecuarios (2011) and described in Appendix 5. Physical data were obtained from the low SR (1.6 cows/ha) and the high SR (2.6 cows/ha) farmlets of the SR experiment reported in Chapter 3, with crossbred Holstein-Jersey cows, average LW of 485 kg, a starting calving date of 1 August (10 weeks calving) and with 1.8 t DM/cow/year of imported supplements for both low and high SR systems. Pasture DM produced on-farm was set to behave stochastically with a normal distribution, with means of 12.1 and 12.2 t DM/ha/year for the low and high SR farmlets, respectively. Milk payout and imported supplement (12 MJ ME/kg DM) price were also set to behave stochastically using normal distributions, with means of $US0.27/kg milk and $US0.16/kg DM supplement. A dry-off policy was implemented so that cows were dried-off individually either at 280 days in milk if milk yield was less than 0.7 kg MS/cow per day, or at 270 days in milk if BCS was less than 4 (NZ scale, 1-10), or at 60 days before next calving. A replacement rate of 28% was assumed.

The performance of each of the systems was stochastically simulated 200 times, and per cow yields were 498 ± 19 and 424 ± 17 kg MS/cow/year for the low and high SR, respectively. Average MS yields were 796 ± 31 kg MS/ha/year in the low SR farm and 1102 ± 44 kg MS/ha/year in the high SR farm systems. The high SR system had higher operating profit per hectare/year ($US750 ± 731) than the low SR system ($US417 ± 620), as an average of all simulations. Figure 2b shows that the high SR system resulted in higher operating profit across the range of milk prices tested. Figure 2b and 2c showed that operating profit was more strongly dependant on milk price than on supplement price.

Simulations in the present Chapter were not designed to compare results from dairy systems in NZ and Argentina. However, it is worth noticing some differences in results and the associated reasons. In the case of simulations for NZ, low input systems (low SR and low supplementation per cow) were compared to high input systems (higher SR and higher supplementation per cow). In Argentina, low SR systems were compared to high SR systems, but with the same level (high) of supplementation per cow, because supplement costs less (relative to the value of milk) than in New Zealand, and is therefore a key input.

Thus, the simulated NZ systems had comparative SR (kg LW/t DM offered) of 93 and 87 kg LW/t DM offered for low and high input systems, respectively; while the simulated Argentine systems had comparative SR of 58 and 75 kg LW/t DM offered for low and high SR systems, respectively. Therefore, a higher MS/ha response was obtained per extra ton of pasture produced/ha for the NZ systems (Figure 1a) than for the Argentine systems (Figure 2a), because of the greater need for feed in the NZ systems. It is interesting to notice that these comparative SR are in the range of those commonly used in each country.

These differences in milk response to pasture produced on-farm explain the higher dispersion of operating profit observed for NZ simulations compared to Argentine simulations, given the stronger dependence on the amount of pasture grown in NZ, which behaved stochastically. In addition the higher ratio of $/kg milk to $/kg supplement for Argentine dairy systems (1.8 ± 0.55) compared to NZ dairy systems (1.1 ± 0.31) explains the higher profitability of increasing SR plus supplementation in Argentina than in to NZ.

Although the simulation was not designed to compare systems between both countries, Figure 1 and 2 show the potential of the e-Dairy model to compare and understand differences in dairy production systems between different countries.

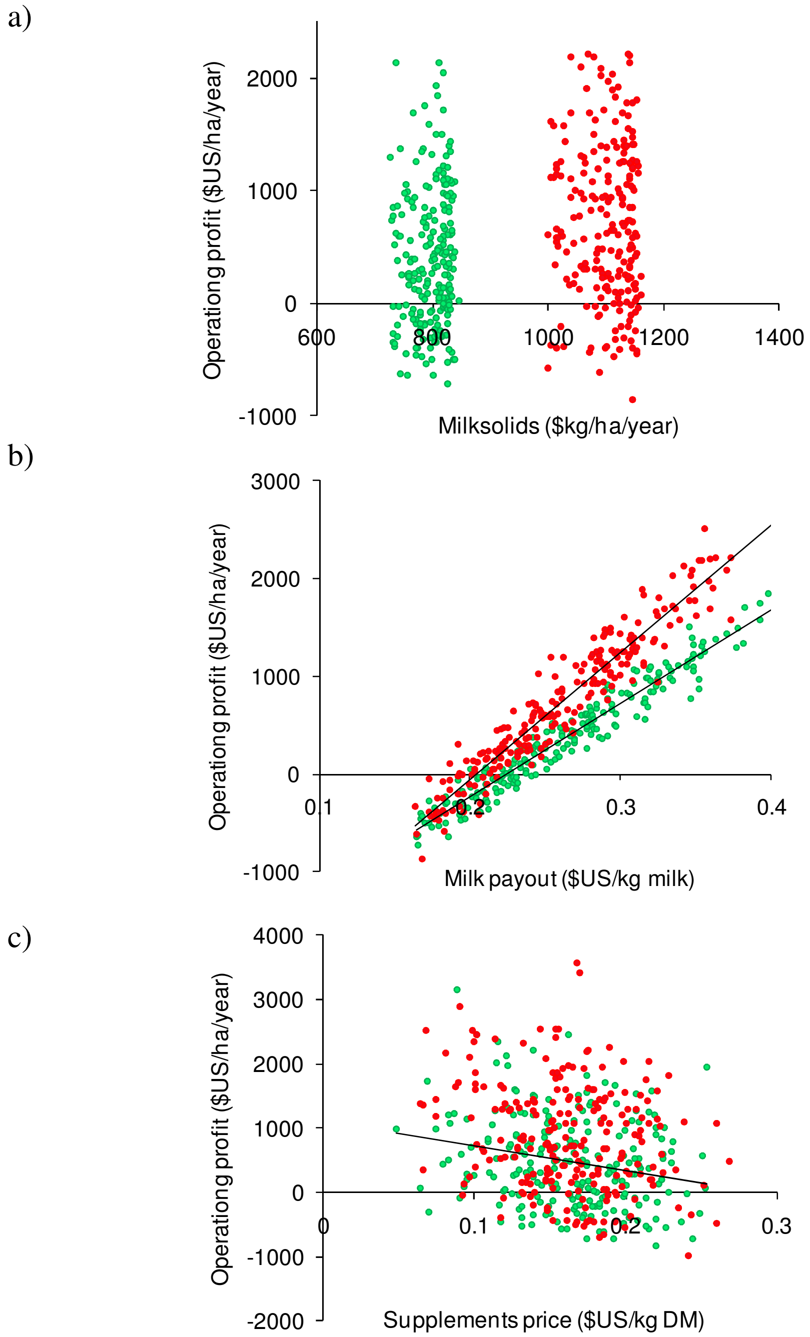


Figure 2 Stochastic simulations (n=200) performed with e-Dairy for physical and economic performance of lucerne-based dairy farms on leased land in Argentina. (●) Low stocking rate systems (1.6 cows/ha) and (●) high stocking rate systems (2.6 cows/ha). For both systems, 1.8 t DM/cow/year of imported supplement was considered. Pasture grown (mean 12.1 t DM/ha/year), milk payout ($US 0.27/kg milk) and supplements price ($US 0.16/kg milk) were allowed to behave stochastically using a normal distribution, while all other variables were held constant.

LIMITATIONS AND FURTHER RESEARCH REQUIRED

Experiments

The farmlet experiment described in Chapter 3, although it is original for lucerne-based dairy systems, explored only three levels of SR using only one type of cow, and the number of cows was not enough to detect reproductive effects of SR. Therefore, further research is required to explore higher levels of SR using different breeds of cows and exploring not only physical and economic outputs but also the associated environmental impact of increased SR, *i.e.*, nutrients leaching, physical soil properties.

The short-term experiment described in Chapter 4, when published, would be the first experiment validating the intake marker LIPE. However, this was validated against the animal performance method, and further validation of this intake marker remains to be done against total collection of faeces for grazing dairy cows.

Modelling

The intake model described in Chapter 5 predicts intake accurately for grazing dairy cows offered relatively low amounts of supplements. However, the accuracy of the model for cows offered high levels of supplementary feed must be tested.

The e-Cow model may not be accurate in the prediction of short-term changes in BCS across lactation, even though BCS at the end of lactation was accurately predicted. As was stated for the intake prediction model (Chapter 5), the dataset used for validation has a reduced range of supplementation levels, and therefore, predictions for cows offered high levels of supplements may not be as accurate as it may underestimate DM intake.

In the e-Cow model, the prediction of milk yield depends on parameters that shape the potential milk yield and the target BCS curve. Parameters for HF cows of NA and NZ genetics are included in the model for both potential milk yield and target BCS curves. However, for cows of different genetic backgrounds, such as Jersey cows, parameters for potential milk yield and target BCS curves will need to be calculated from experimental datasets.

The e-Dairy model described in Chapter 7 does not link BCS to reproduction, and does not include health issues. However, the effects of BCS on reproduction could be implemented in future work by relating BCS levels to the probabilities of pregnancy. Likewise, the effect of health problems on the performance of cows could be implemented with a probabilistic approach supported by experimental data of the main health problems of dairy herds, such us mastitis and lameness.

At the current stage of development, the e-Dairy model is based only on ME. However, there may be excess of protein in leafy spring and autumn pastures, or lack of protein in diets with high proportion of maize silage, in which cases, the inclusion of a protein balance would improve predictions. Furthermore, nitrogen partitioning within the cow could be estimated, in order to simulate nitrogen excretion. Climatic effects are not accounted for at the current stage of development of the e-Dairy model. It could be improved by including factors such as air temperature and humidity which may impact on production and reproduction because of the potential associations with heat stress.

Two important features of the e-Dairy model are its ability to randomly generate individual cows with internally correlated variables and the ability to account for genotype by environment effects, since it includes the e-Cow model. These two features are the basis for future work on ‘simulated progeny tests’. These make it possible to explore whether different selection objectives can differ in their long term results when applied to different ‘feeding environments’, with the ability to account for stochasticity, makings the model robust in the face of uncertainty.

The e-Dairy model, which integrates all the modelling chapters of this thesis, could be adjusted to be used in other animal production systems such as dairy goats or dairy sheep. The main adjustments required would be related to the parameters defining the potential milk yield and BCS curves, as well as the parameters related to the limitation to potential herbage intake.

GENERAL CONCLUSIONS

The main conclusions from this thesis are the following:

1. The review chapter integrated published information about HF strain trials from NZ, Ireland and Australia, and reported the effect of the percentage of NA genetics on the milk response to supplementation and on the pregnancy rate. It was concluded that, as the proportion of NA genetics increased from 20% to 80%, milk response to supplements increased by 0.3 kg milk/kg DM supplement consumed, while pregnancy rate decreased by 13%.

2. The meta-analysis performed in the review chapter integrated findings from 31 previous experiments using ryegrass-based pastures. It was found that HA for maximum HI per cow were 78.4 and 30.9 kg DM/day when HA is expressed at ground level and 4 cm above ground level, respectively.

3. The experiment reported in Chapter 3 is the first experiment that explored the effects of SR for lucerne-based dairy systems. This study showed that an increase in SR of 1 cow/ha together with an increase in 1.8 t DM/ha/year of imported supplement resulted in an increase in 2.4 t DM/ha/year of pasture consumed and 5,840 kg/ha/year of milk produced by cows offered a fixed amount of supplement per lactation at all SR.

4. The experiment reported in Chapter 4 compares HI measured with an indigestible intake marker (LIPE®) versus estimates of HI from animal performance. Estimations with both methods had a moderate correlation. Results also showed that the intake marker method detected differences in HI between HA treatments, while the sward cutting method did not.

5. Two simulation models were developed, the e-Cow (an animal model) and the e-Dairy (a whole-farm model). The main strengths of e-Cow are its ability to predict the daily and whole-lactation performance of dairy cows at grazing with high accuracy in comparison to previous models which also account for genetic differences for grazing dairy cows. In addition, the sensitivity to genetic by environment interaction is an important feature of e-Cow. The approach used to define the potential milk yield of the cow and the equations used to predict

herbage DM intake at grazing should allow the use of e-Cow in many countries with temperate pastures.

6. The e-Dairy model was designed to predict the physical and economic performance of milk production systems and to explore the interactions between genetic merit, supplementation, stocking rate and market prices for systems using either ryegrass-based or lucerne-based pastures. The e-Dairy model is original because it simulates individual cows, randomly generated on the basis of phenotypic variance and co-variances from experimental datasets. Additionally, it is able to simulate stochastically and simultaneously some of the key dairy system variables including pasture grown, genetic merit of cows, milk and supplement prices. Its versatility in terms of defining calving patterns, i.e., any weekly pattern, type of pasture, i.e., ryegrass-based or lucerne-based, and genetic merit of cows makes the model useful for different types of grazing dairy systems.

7. The ability of the e-Dairy model to randomly generate individual cows with internally correlated variables, together with its ability to account for genotype by environment interactions, are the basis for future work on 'simulated progeny tests' of bulls under different selection objectives and selection schemes.

8. Stochastic simulations reported in the present chapter suggest that for ryegrass-based NZ dairy systems, the increase in SR from 2.8 to 3.5 cows/ha together with an increase in supplements imported from 0.15 to 1.45 t DM/cow/year can be profitable when milk price is higher than $NZ5.5/kg MS. Similarly, simulations suggest that, for lucerne-based dairy systems in Argentina, the increase in SR from 1.6 to 2.6 cows/ha, with a fixed amount of imported supplements per cow at 1.8 t DM/cow/year, would increase operating profit across the range of milk prices tested ($US 3.3 ± 0.84/kg MS).

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Appendix 1

Description of Equations and Visual Basic procedures

used in Chapter 6 (e-Cow model)

APPENDIX 1

Iterative procedure used to calculate metabolisable energy (ME) partitioning (description of iteration depicted in Figure 1, Chapter 6).

The procedure is written in Visual Basic programming language as follows:

```
Sub Iteration
      .MEmilk = .ME Potential Milk Yield
      .MEBalance = .Daily(Day).MEItkTotal - (.MEmilk + .MEfromToBCSChange  +
      .MEm +  .MEp + MEgr)
      Do
         If .MEBalance > 0 Then
             .ME to Milk Yield = .MEmilk * 1.01
                 If .MEfromToBCSChange > 0 then
                         .MEfromToBCSChange = .MEfromToBCSChange * 1.01
                 Else
                         .MEfromToBCSChange = .MEfromToBCSChange * 0.99
                 End if
         Else
             .ME to Milk Yield = .MEmilk * 0.99
                 If .MEfromToBCSChange > 0 then
                         .MEfromToBCSChange = .MEfromToBCSChange * 0.99
                 Else
                         .MEfromToBCSChange = .MEfromToBCSChange * 1.01
                 End if
         End if
     .MEBalance = .Daily(Day).MEItkTotal - (.MEmilk + .ME from To BCS Change +
     .MEm + .MEp + MEgr)
           Loop Until Abs(.MEBalance) <= 1
        End Sub
```

Energy requirements for live weight change in lactating animals

The energetic cost associated with LW change due to changes in BCS (LW_0) is calculated as follows:

ME per 1 kg LW gain (MEKgLwtGain) = (10.1 + 1.976 x BCS) / Kl

ME available from 1 kg LW loss (MEKgLwtLoss) = (10.1 + 1.976 x BCS) x 0.84 / Kl

Energy requirements for live weight change in non-lactating animals

ME per 1 kg LW gain (MEKgLwtGain) = (10.1 + 1.976 x BCS) / KGainDry

ME available from 1 kg LW loss (MEKgLwtLoss)= (10.1 + 1.976 x BCS) x 0.84 / Kl

KGainDry = efficiency of use of ME for live weight gain = 0.042 x MEDiet + 0.006

EGRAZE: additional energy expenditure of a grazing animal compared with a similar housed animal:

EGRAZE (MJ net energy d^{-1}) = $\left[[0.06 \times HI(0.9 - D)] + \left(\frac{0.05T}{GF + 3} \right) \right] W$

HI = dry matter intake (kg/cow/day) from pasture

D = dry matter digestibility (decimal)

T = 1.0 or 1.5 or 2.0 for respectively level, undulating or hilly terrain (assumed to be 1 for dairy cows and 1.5 for sheep and beef cattle)

GF = availability of green forage (t DM/ha) = assumed at 1.5

Energy requirements for gestation (MEp)

MEp = Eg / 0.13 x .Wb / 40

Et = 10 ^ (151.665 - (151.64 x Exp(-0.0000576 x PregDays)))

Eg = 0.025 x .Wb x Et x 0.0201 x Exp(-0.0000576 x PregDays)

Wb = calf birth weight (kg)

PregDays= days after conception

LIPID Model:

BCS standard = 5

LW at BCS standard = LW at calving / (1 - 0.1 x (BCS standard – BCS at calving))

kg LW per unit BCS = 0.1 x LW at BCS standard

LW at BCS 3 (scale 1-5) = LW at BCS standard – (2 x kg LW per unit BCS)

Gut fill = 0.15 x LW at BCS 3

Empty body weight = LW at BCS 3 x (1- 0.15)

Conversion between BCS scales (Roche et al., 2009):

BCS_USA = 1.5 + 0.32 x BCS_NZ

BCS_USA = BCS expressed in US scale (1-5)

BCS_NZ = BCS expressed in NZ scale (1-10)

Appendix 2

Web-based version of the e-Cow model (Chapter 6):

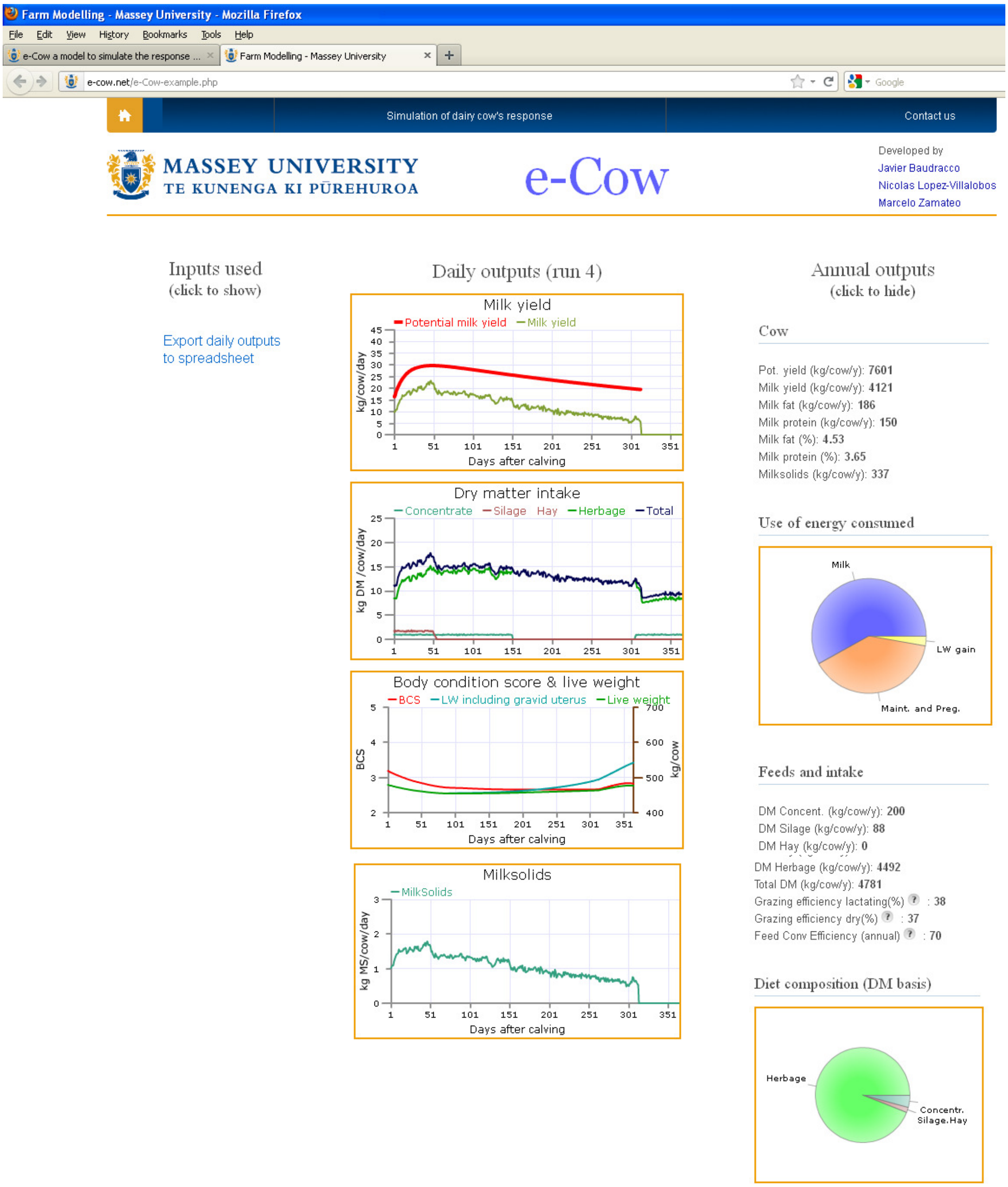
Inputs and outputs screens of the

preliminary web site

APPENDIX 2

Inputs screen of the web-based version of the e-Cow model, preliminary web site.

Outputs screen of the web-based version of the e-Cow model, preliminary web site.



Appendix 3

Phenotypic (co)variance matrix between the traits used to define the genetic merit of cows in the e-Dairy model (Chapter 7)

APPENDIX 3

Table 1 Phenotypic (co)variance matrix between the traits used to define the genetic merit of North American Holstein Friesian cows. The dataset used to calculate variances and covariances was obtained from Macdonald *et al.* (2008a).

		Potential milk yield	LW at calving	Parameters of Wilmink function (% milkfat)			Parameters of Wilmink function (% milkprotein)		
				a	*b*	*c*	*a*	*B*	*c*
Potential milk yield		1430232.8							
LW at Calving		47387.15	4212.4248						
Parameters of Wilmink function (% milkfat)	*a*	-156.11219	0.2312288	0.2143214					
	b	383.99047	16.766320	-0.3021659	1.7836865				
	c	0.1757981	-0.0037495	-0.0005683	0.0012392	0.0000080			
Parameters of Wilmink function (% milkprotein)	*a*	29.325541	-2.5544359	-0.0299304	0.0162241	0.0000212	0.1040049		
	b	77.500622	4.9462307	0.0392871	-0.0067201	0.0001537	-0.1755727	0.8318738	
	c	0.3503854	0.0410408	0.0001038	-0.0000188	0.0000003	-0.0004894	0.0009804	0.0000045

Table 2 Phenotypic (co)variance matrix between the traits used to define the genetic merit of New Zealand Holstein Friesian cows. The dataset used to calculate variances and covariances was obtained from Macdonald *et al.* (2008a).

		Potential milk yield	LW at calving	Parameters of Wilmink function (% milkfat)			Parameters of Wilmink function (% milkprotein)		
				a	*b*	*c*	*a*	*B*	*c*
Potential milk yield		1077976.8							
LW at Calving		34145.295	3382.3566						
Parameters of Wilmink function (% milkfat)	*a*	52.349624	-1.0773607	0.1010250					
	b	-32.168660	1.9453413	-0.1789877	0.9785661				
	c	0.1808006	0.0249045	-0.0003618	0.0007337	0.0000035			
Parameters of Wilmink function (% milkprotein)	*a*	56.519878	-0.9755409	0.0971430	-0.1637328	-0.0003496	0.0972466		
	b	-44.014585	1.4954282	-0.1637328	0.9042393	0.0006741	-0.1625157	0.9060720	
	c	0.1786417	0.0251085	-0.0003496	0.0006741	0.0000035	-0.0003481	0.0006703	0.0000035

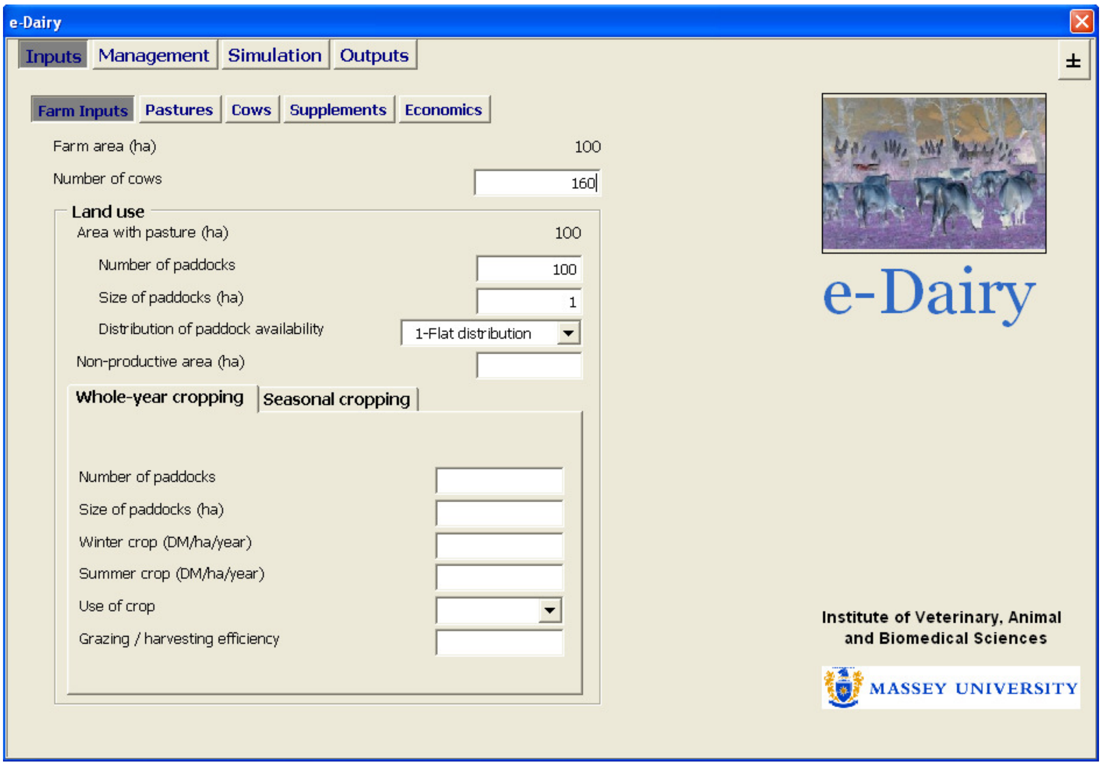
Table 3 Phenotypic (co)variance matrix between the traits used to define the genetic merit of crossbred Holstein-Jersey cows. The dataset used to calculate variances and covariances was obtained from Baudracco *et al.* (2011b).

		Potential milk yield	LW at calving	Parameters of Wilmink function (% milkfat)			Parameters of Wilmink function (% milkprotein)		
				a	*b*	*c*	*a*	*b*	*c*
Potential milk yield		1311828.6							
LW at Calving		24122.148	3595.8456						
Parameters of Wilmink function (% milkfat)	*a*	-125.79220	-4.3192100	0.5094826					
	b	-1.0302056	-0.0102211	-0.0014789	0.0000115				
	c	-423.35243	1.7638296	-1.0061231	0.0054040	8.1105395			
Parameters of Wilmink function (% milkprotein)	*a*	-89.412664	-4.3665463	0.0992034	-0.0001241	-0.0718973	0.0818793		
	b	-0.1671615	0.0178905	-0.0001127	0.0000019	0.0005169	-0.0002224	0.0000020	
	c	24.441355	5.3622383	-0.1536055	0.0007579	1.1064297	-0.1069614	0.0006132	0.7198653

Appendix 4

Interface screens of the e-Dairy model

APPENDIX 4


e-Dairy
Inputs
Management
Simulation
Outputs
Farm Inputs
Pastures
Cows
Supplements
Economics
Farm area (ha)
100
Number of cows
160
Land use
Area with pasture (ha)
100
Number of paddocks
100
Size of paddocks (ha)
1
Distribution of paddock availability
1-Flat distribution
Non-productive area (ha)
Whole-year cropping
Seasonal cropping
Number of paddocks
Size of paddocks (ha)
Winter crop (DM/ha/year)
Summer crop (DM/ha/year)
Use of crop
Grazing / harvesting efficiency
e-Dairy
Institute of Veterinary, Animal and Biomedical Sciences
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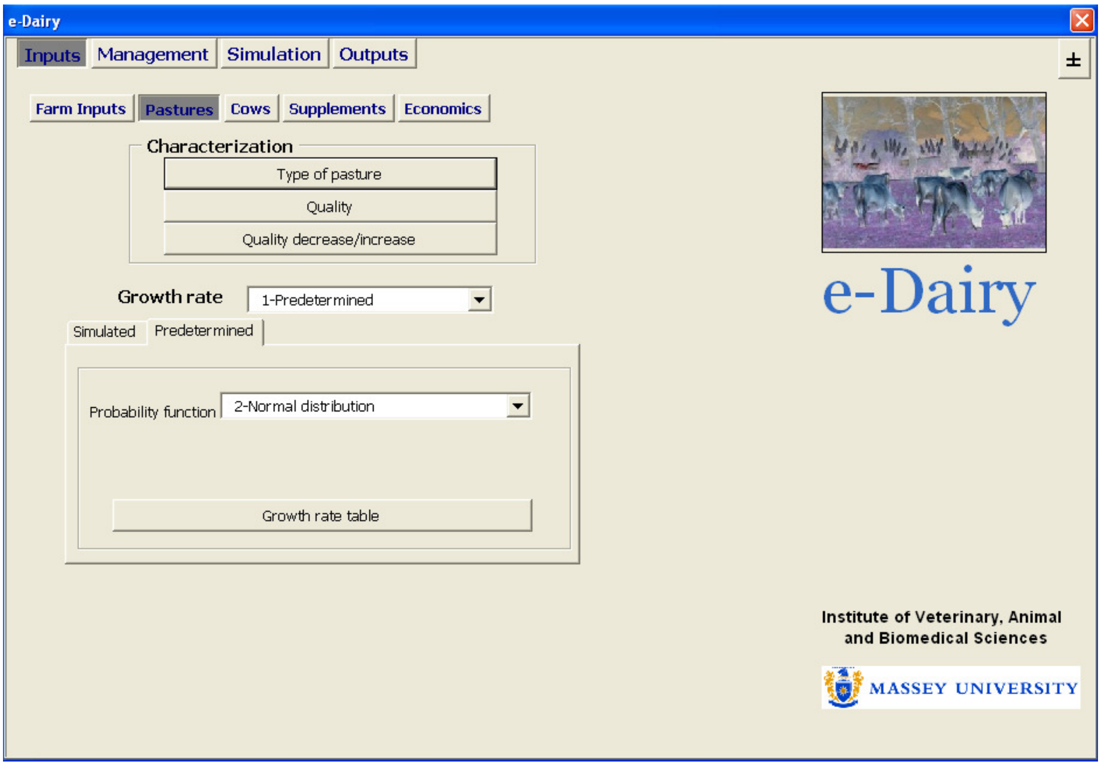
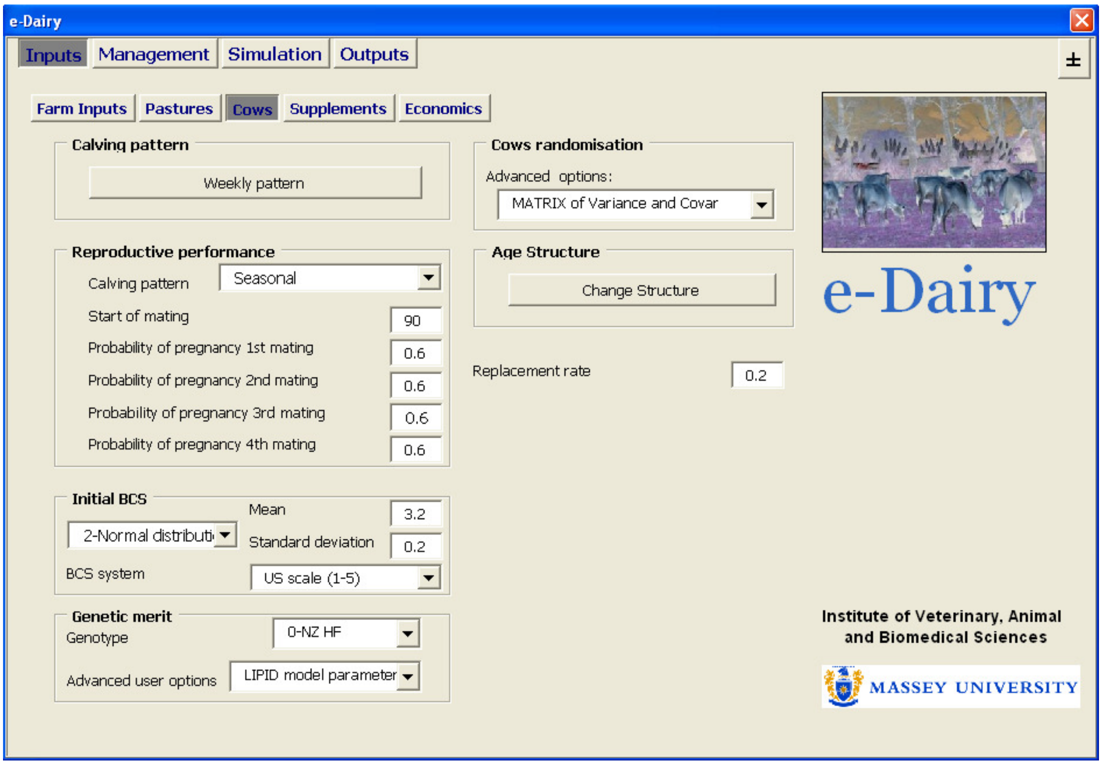
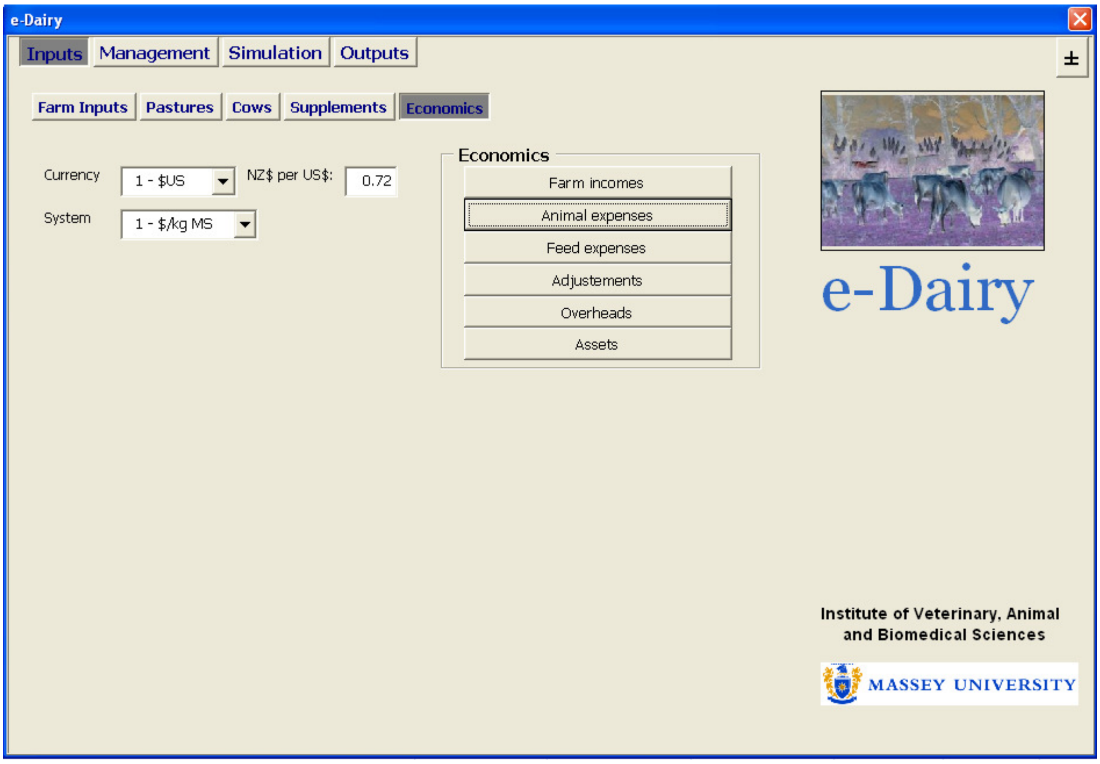
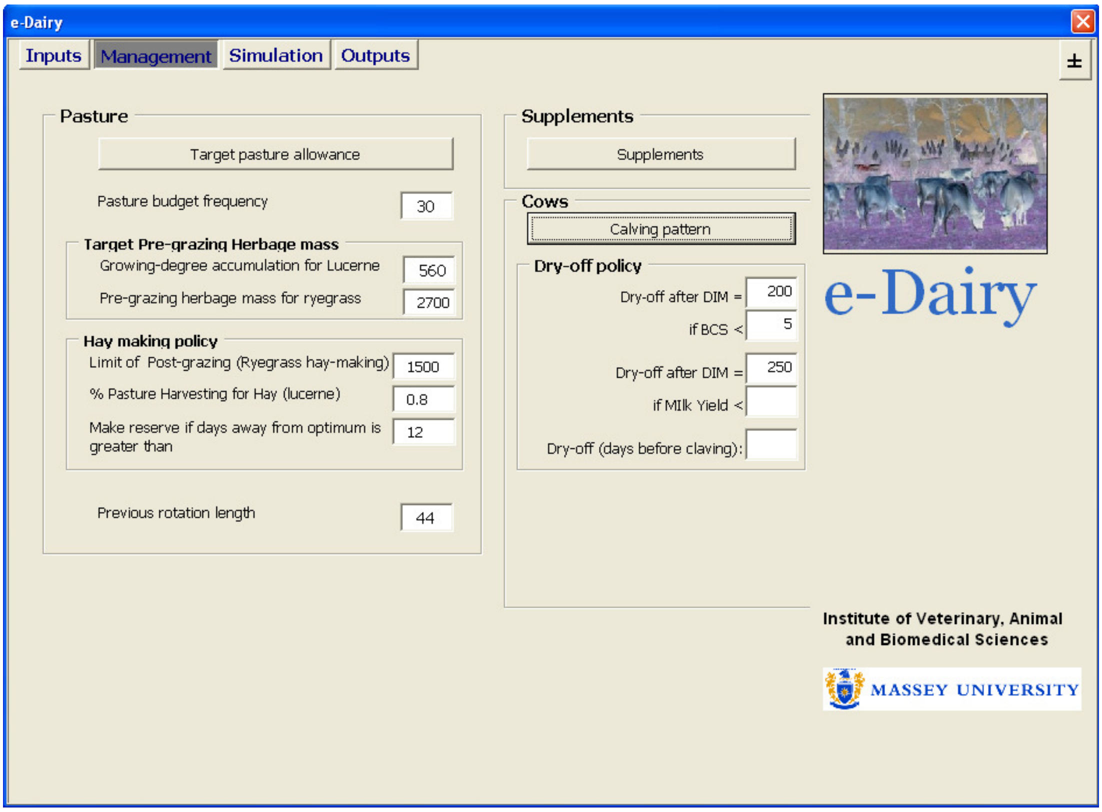
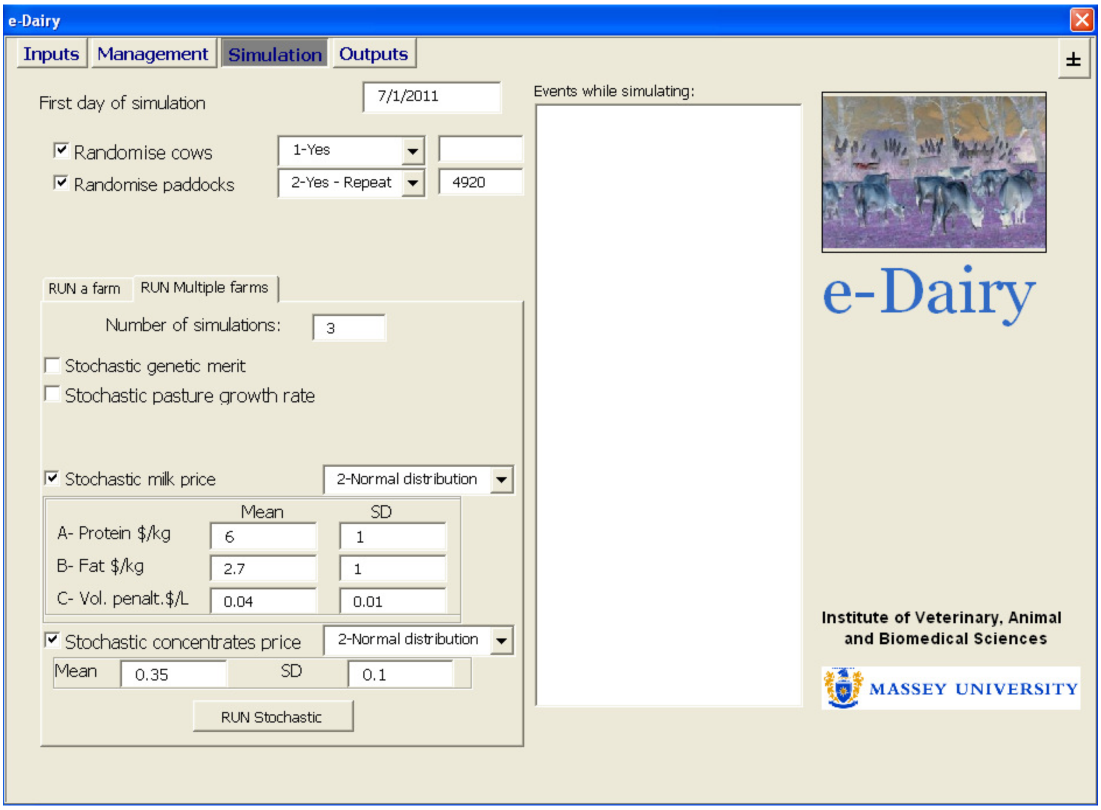

e-Dairy
Inputs
Management
Simulation
Outputs
Farm Inputs
Pastures
Cows
Supplements
Economics
Characterization
Type of pasture
Quality
Quality decrease/increase
Growth rate
1-Predetermined
Simulated
Predetermined
Probability function
2-Normal distribution
Growth rate table
e-Dairy
Institute of Veterinary, Animal and Biomedical Sciences
MASSEY UNIVERSITY


e-Dairy
Inputs
Management
Simulation
Outputs
Farm Inputs
Pastures
Cows
Supplements
Economics
Calving pattern
Weekly pattern
Cows randomisation
Advanced options:
MATRIX of Variance and Covar
Reproductive performance
Calving pattern
Seasonal
Start of mating
90
Probability of pregnancy 1st mating
0.6
Probability of pregnancy 2nd mating
0.6
Probability of pregnancy 3rd mating
0.6
Probability of pregnancy 4th mating
0.6
Age Structure
Change Structure
Replacement rate
0.2
Initial BCS
Mean
3.2
2-Normal distributi
Standard deviation
0.2
BCS system
US scale (1-5)
Genetic merit
Genotype
0-NZ HF
Advanced user options
LIPID model parameter
e-Dairy
Institute of Veterinary, Animal and Biomedical Sciences
MASSEY UNIVERSITY


e-Dairy
Inputs
Management
Simulation
Outputs
Farm Inputs
Pastures
Cows
Supplements
Economics
Currency
1 - $US
NZ$ per US$:
0.72
System
1 - $/kg MS
Economics
Farm incomes
Animal expenses
Feed expenses
Adjustements
Overheads
Assets
e-Dairy
Institute of Veterinary, Animal and Biomedical Sciences
MASSEY UNIVERSITY


e-Dairy
Inputs
Management
Simulation
Outputs
Pasture
Target pasture allowance
Pasture budget frequency
30
Target Pre-grazing Herbage mass
Growing-degree accumulation for Lucerne
560
Pre-grazing herbage mass for ryegrass
2700
Hay making policy
Limit of Post-grazing (Ryegrass hay-making)
1500
% Pasture Harvesting for Hay (lucerne)
0.8
Make reserve if days away from optimum is greater than
12
Previous rotation length
44
Supplements
Supplements
Cows
Calving pattern
Dry-off policy
Dry-off after DIM =
200
if BCS <
5
Dry-off after DIM =
250
if Milk Yield <
Dry-off (days before claving):
e-Dairy
Institute of Veterinary, Animal and Biomedical Sciences
MASSEY UNIVERSITY


e-Dairy
Inputs
Management
Simulation
Outputs
First day of simulation
7/1/2011
Randomise cows
1-Yes
Randomise paddocks
2-Yes - Repeat
4920
Events while simulating:
RUN a farm
RUN Multiple farms
Number of simulations:
3
Stochastic genetic merit
Stochastic pasture growth rate
Stochastic milk price
2-Normal distribution
Mean
SD
A- Protein $/kg
6
1
B- Fat $/kg
2.7
1
C- Vol. penalt.$/L
0.04
0.01
Stochastic concentrates price
2-Normal distribution
Mean
0.35
SD
0.1
RUN Stochastic
e-Dairy
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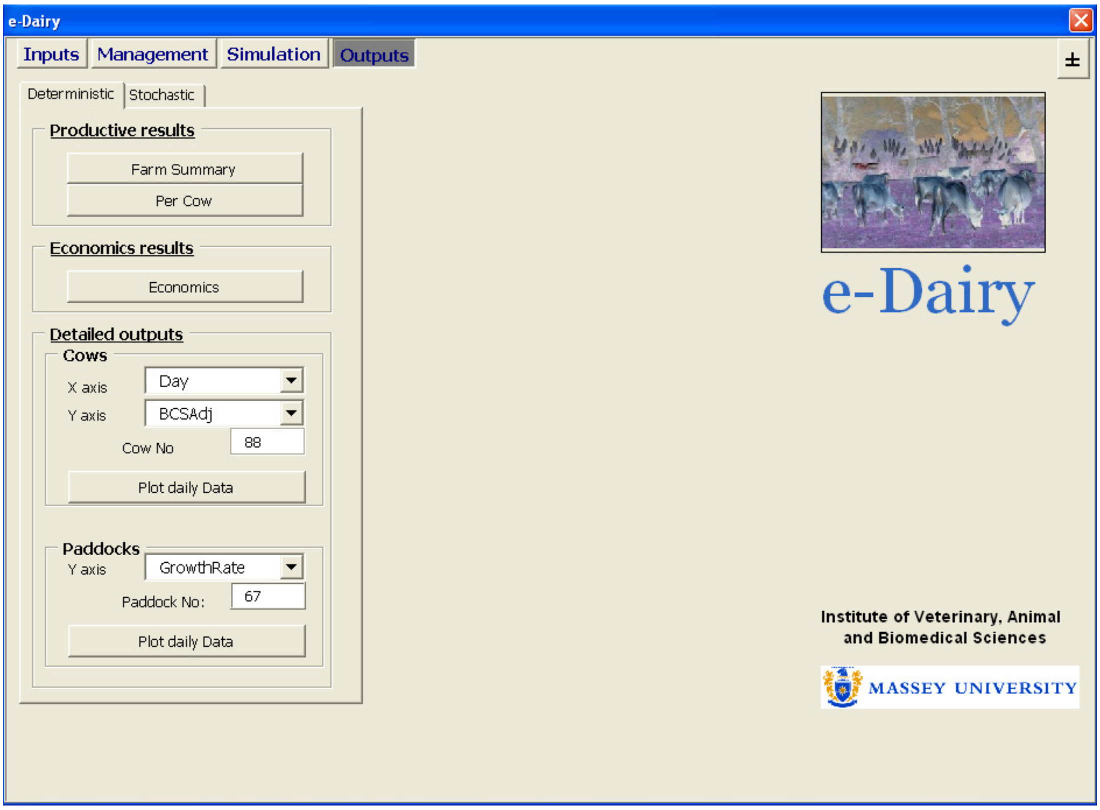
e-Dairy
Inputs
Management
Simulation
Outputs
Deterministic
Stochastic
Productive results
Farm Summary
Per Cow
Economics results
Economics
Detailed outputs
Cows
X axis
Day
Y axis
BCSAdj
Cow No
88
Plot daily Data
Paddocks
Y axis
GrowthRate
Paddock No:
67
Plot daily Data
e-Dairy
Institute of Veterinary, Animal and Biomedical Sciences
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Appendix 5

Inputs required to calculate dairy operating profit

APPENDIX 5

Inputs required to calculate Dairy Operating Profit for ryegrass-based dairy system in New Zealand, simulated in Chapters 7 and 8.

	2.8 cows/ha $NZ	3.5 cows/ha $NZ
Effective area	128	128
Number of cows	358	448
Replacement rate	20%	20%
Land Use		
Area with pasture	128	128
Area with summer crop	-	-
Area with winter crop	-	-
Litres milk produced/ha (average simulated)	11,762	19,044
Kg milksolids produced/ha (average simulated)	941	1,534
1 - Farm incomes		
Milk income		
System 1		
A - Milk protein price ($/kg)	8.90	8.90
B - Milk fat price ($/kg)	3.40	3.40
C - Milk volume penalty ($/L)	0.038	0.038
Other incomes		
Sale of calves ($/calf)	40	40
Sale of heifers ($/heifer)	-	-
Sale of cows ($/kg LW)	1.5	1.5
Feed Inventory Adjustments	-	-
Hay Stock adjustment ($/kg hay)	0.24	0.24
Silage Stock adjustment ($/kg Silage)	0.35	0.35

2 - Animal expenses	$NZ	
Labour[1]		
% milk payout (option 1)		
$/cow/year (option 2)	170	170
Animal Health ($/cow)	76	76
Breeding and herd testing ($/cow)	44	44
Farm dairy expenses ($/cow)	20	20
Electricity ($/cow)	40	40
Freight (% Stock sale income)	8%	8%
Others ($/cow)	120	120
Pre-weaning costs ($/calf)	306	306
Young stock grazing off		
$/heifer/month	28	28
3 - Feed expenses		
Pasture renovation ($/ha pasture)	35	35
Fertiliser ($/ha pasture)	230	230
Weed and pest control ($/ha Pasture)	30	30
Crop expenses		
$/ha summer crop	-	-
$/ha winter crop	-	-
Winter Cow Grazing-off		
$/cow/month	-	-
Number of months	-	-
Number of cows	-	-
Concentrates bought in ($/kgDM)	0.45	0.45
Hay bought in (kg DM/year)	0.24	0.24
Silage bought in (kg DM/year)	0.35	0.35
Hay Making ($/kg DM)	0.12	0.12
Silage Making and feeding ($/kg DM)	0.20	0.20
4 - Overheads		
Repairs and maintenance ($/ha/year)	304	304
Vehicle expenses ($/ha/year)	180	180
Administration ($/ha/year)	120	120
Standing charges ($/ha/year)	155	155
Depreciation ($/cow/year)	450	450
Land Leasing ($/ha/year)	-	-
Capital cost of land (%)[2]	-	-
Price of 1 hectare of Land[3]	-	-
5 – Assets		
Farm Assets ($/cow)[3]	-	-

[1]Does not includes unpaid labour and management (Labour adjustment).
[2]No interest included to calculate Dairy Operating Profit.
[3]Return on Assets was not calculated in the simulation.

Inputs required to calculate Dairy Operating for lucerne-based dairy system in Argentina, simulated in Chapter 8.

	1.6 cows/ha $US	2.6 cows/ha $US
Effective area	100	100
Number of cows	160	260
Replacement rate	28%	28%
Land Use		
Area with pasture	87	87
Area with summer crop	13	13
Area with winter crop	-	-
Litres milk produced/ha (average simulated)	10,848	15,046
Kg milksolids produced/ha (average simulated)	796	1,102
1 - Farm incomes		
Milk income		
System 2		
Milk Price ($/Litre)	0.27	0.27
Other incomes		
Sale of calves ($/calf)	20	20
Sale of heifers ($/heifer)	-	-
Sale of cows ($/kg LW)	1	1
Feed Inventory Adjustments		
Hay Stock adjustment ($/kg hay)	0.09	0.09
Silage Stock adjustment ($/kg Silage)	0.15	0.15

2 - Animal expenses	$US	
Labour[1]		
% milk payout (option 1)	12%	12%
$/cow/year (option 2)	-	-
Animal Health ($/cow)	81	81
Breeding and herd testing ($/cow)	42	42
Farm dairy expenses ($/cow)	43	43
Electricity ($/cow)	30	30
Freight (% Stock sale income)	8%	8%
Others ($/cow)	80	80
Pre-weaning costs ($/calf)	180	180
Young stock grazing off		
$/heifer/month	-	-
3 - Feed expenses		
Pasture renovation ($/ha pasture)	105	105
Fertiliser ($/ha pasture)	20	20
Weed and pest control ($/ha Pasture)	32	32
Crop expenses		
$/ha summer crop	370	370
$/ha winter crop	-	-
Winter Cow Grazing-off		
$/cow/month	-	-
Number of months	-	-
Number of cows	-	-
Concentrates bought in ($/kgDM)	0.16	0.16
Hay bought in (kg DM/year)	0.11	0.11
Silage bought in (kg DM/year)	0.18	0.18
Hay Making ($/kg DM)	0.06	0.06
Silage Making and feeding ($/kg DM)	0.10	0.10
4 - Overheads		
Repairs and maintenance ($/ha/year)	168	168
Vehicle expenses ($/ha/year)	72	72
Administration ($/ha/year)	94	94
Standing charges ($/ha/year)	114	114
Depreciation ($/cow/year)	104	104
Land Leasing ($/ha/year)	540	540
Capital cost of land (%)[2]	-	-
Price of 1 hectare of Land[3]	-	-
5 – Assets		
Farm Assets ($/cow)[3]	-	-

[1]Does not includes unpaid labour and management (Labour adjustment).
[2]No interest included to calculate Dairy Operating Profit.
[3]Return on Assets was not calculated in the simulation.