Systems, component, and modelling studies of pasture-based dairy systems in which the cows calve at different times of the year

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ABSTRACT

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The New Zealand's dairy system is characterised by a concentrated calving period in late winter-early spring, which aims to synchronise cows' feed requirements with the seasonal pattern of pasture growth, but which also results in an uneven distribution of milk supply to the factories. Changing the calving season of some herds from spring into autumn could improve the overall efficiency of the dairy industry. However, pasture-based autumn-calving systems are usually perceived to be less "efficient", because of the lack of synchrony between feed supply (grazed pasture) and feed requirements. One conclusion of the literature review (Chapter 1) was to hypothesise that autumn- and spring-calving systems would perform at similar levels provided that sufficient supplementary feed was available during wintertime. This thesis integrated three experimental approaches (system, component, and modelling) in order to test the above hypothesis, and to investigate the physical performance of pasture-based dairy systems that differed in their calving dates. A 3-year system study conducted at No 1 Dairy Farm, Massey University, in which autumn, spring, and autumn/spring calving systems were compared, showed that all systems achieved similar performances and overall efficiencies (Chapter 2). A key factor for this was the greater total yields by the autumn-calved cows, due mainly to their greater yields in mid and late lactation and their longer lactations (Chapter 3). A new technique that combines the n-alkanes and ^{13}C methods in order to quantify herbage and maize silage DM intakes by individual grazing cows which are given access to the silage as a group, was developed and validated (Chapter 4), and re-evaluated in a separate study (Chapter 5). Overall, individual cows differed considerably in their intakes of maize silage DM, but this variation was not always related to variation in milk yields. An innovative, dynamic, interactive simulator of seasonal pasture-based dairy farms (IDFS) was developed as part of this thesis (Chapter 6). The model allows computer experiments to be run, with pastures and cows managed on the basis of logical decision rules; therefore, it resembles real farm management. The user makes decisions (which paddocks are to be grazed, pre- and post-grazing herbage mass, supplement feeding, etc) continuously, and can see the impact of his/her management decisions on the graphical interface provided. Based on comparisons with actual data, it was concluded that IDFS simulates the main components of seasonal dairy farms with reasonable realism (Chapter 7), although the model is at an early stage of development and has not been completely validated. In conclusion, this thesis has 1) demonstrated that pasture-based systems with contrasting calving dates can achieve similar physical performances provided that supplementary feeds are available, and 2) developed two new tools (quantification of herbage and maize silage intakes by individual cows, and the IDFS model) that can be applied in future systems research.

Dedicated to Valeria

PREFACE

This thesis is the result of a project that originated from debate about the very basis of the New Zealand dairy industry: the need to synchronise feed supply (rate of herbage growth) with feed demand (cows' requirements) by means of concentrating the calving season in early spring. Is this the best alternative for all farmers? Will farmers reduce the overall physical efficiency of their systems if they decide to change the calving season? Will they need to use increased quantities of supplementary feed? These and many other related questions, all of them with important implications for farmers in particular and for the whole industry in general, played a key role in the initiation of this project.

However, research is concerned not only with *what* questions are to be asked, but also with *how* the problem is to be addressed and the questions are to be answered. I started this project with the idea of just comparing different pasture-based systems that would differ in their milk supply pattern. However, it soon became obvious that the complexity involved in these 'real-world' systems, would make it very difficult to fully understand the systems and to reach meaningful conclusions. I needed to apply other tools to the systems comparison in order to gain more insight into the main factors and interactions that govern those systems. It was then disappointing to discover that research methodologies for systems studies were not straightforward or readily available, and that different research approaches, such as systems studies, component or analytical research, and modelling studies, did not appear to have been integrated in the past. That is why I integrated these three approaches with the aim of addressing the questions at the systems level, as well as contributing to the research methodology in the field.

This thesis is the result of these three approaches to the study of the systems. It comprises results that range from comparisons of the whole-farm systems, through the evaluations of different methods designed to improve the analysis of some key components of the systems, to finish with the development and evaluation of an innovative dairy farm simulator model. Each of these studies is presented as a self-explained unit that has already been, with one exception, either published in, or submitted to a refereed-scientific journal. Each single paper is presented in a form which is as close as possible to the original publication. However, in order to ensure a better and more logical flow in the text, some minor changes were necessary to make the ~~thesis~~ into chapters of the thesis.

papers

The 3-year systems study, which provided the framework for this thesis, was jointly funded by the Technology for Business Growth (TBG) program of The Foundation of

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Alastair MacDonald is the Project Manager of Agricultural Services at Massey University. Alastair has not been a formal supervisor of my thesis but he should have been. Alastair gave me so many opportunities and helped me so much during these years with both the research project and my personal life matters that I am unable to recall them all. Alastair has been always concerned about my wellbeing as well as that of my family and he always has had time to listen and help. Tell Alastair that you have a problem and he would stop anything he was doing to listen to you, no matter how busy he was....Better still, he will sort out your problem! He is, as he calls himself sometimes, a "facilitator" and in fact, I have never seen any other person with such enthusiasm and expertise to work out problems. Thank you Alastair, thank you very much indeed for all your help and support during these years. I'll see you back in Mar del Plata!

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Yani

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General Introduction

1. Introduction

In the pasture-based dairy systems used in New Zealand, the cows' requirements (i.e. the systems' demand) are synchronised with the pasture growth curve (i.e. the systems' supply) in order to achieve the highest possible biological efficiency with the 'lowest' possible cost of production (Holmes *et al.* 1987). Because of this, one of the main features of the New Zealand dairy industry is the concentration of calving in late winter-early spring, which allows this synchronisation to be achieved while minimising the need for supplementary feeds (Sheath and Clark, 1996).

One of the consequences of these systems is the very short lactation lengths (e.g. 223 days in 1996/97 season) achieved by the New Zealand's dairy cows (Livestock Improvement Corporation, 1997). These cows are normally dried off in late summer-early autumn, because they need to regain body condition score for the subsequent lactation, and farmers need to accumulate pasture on their farms before the winter period. This situation has created great interest in New Zealand in the utilisation of supplementary feeds for extending lactation lengths, and several research projects were initiated to investigate the issue (e.g. Clark, 1993). Since then, the average days in milk of the New Zealand cows has increased (Livestock Improvement Corporation, 1998), with a concomitant increase in the use of supplements, in particular grass and maize silage (Penno and Kolver, 2000).

However, once the amounts of supplementary feeds used in the system achieve a certain level, the maintenance of a concentrated calving pattern in early spring is likely to become less important (Penno and Kolver, 2000), because use of supplementary feed makes it possible to supply feed at any time of the year. Furthermore, some previous studies suggest that even when relatively small amounts of supplements are utilised in the systems, milk can be produced at any time of the year with similar overall efficiency to that achieved by spring calving systems (Thomas *et al.* 1985; Ryan *et al.* 1997). The general hypothesis of the present work, therefore, is that contrasting pasture-based dairy systems in which cows calve in the spring, autumn or in both seasons, can produce similar amounts of milk and milksolids per hectare, and achieve similar levels of physical efficiency.

However, testing hypotheses about whole farm systems is a difficult task, because all the systems components are related to at least one or several others, resulting in a very large number or interactions and feed-back mechanisms acting simultaneously (McCall *et al.* 1994).

There are basically three different approaches for studying the behaviour of whole farm systems or their main factors and interactions: component or analytical-synthetic research, experimental systems research and systems research by modelling analyses, or "systemic modelling". In the analytical-synthetic approach, the "system" is reduced to its parts or components, and the mechanistic understanding of these components is used to explain the whole system (Kristensen and Sorensen, 1990). In contrast, experimental systems research studies the behaviour of systems as they exist in the 'real-world', including all their interactions and feed-back mechanisms. Finally, modelling analysis or "systemic modelling" explains real systems by observing them and modelling their input/output relationships (Kristensen and Sorensen, 1990; Sorensen and Kristensen, 1993), an approach which is based on the systems theory of Bertalanffy (1973).

All the above approaches have advantages and disadvantages. Component research can be criticised because once a factor is isolated from the rest of the system, its interactions with other components in the system remain unknown (McCall *et al.* 1994). Field systems research can be criticised because of its lack of accuracy in distinguishing between cause and effect in the main relationships, and system modelling can be criticised because it is a 'simplified representation of the real system'. Although a combination of the above approaches has been advocated (e.g. Bawdens *et al.* 1991), this has not occurred in actual experiments, suggesting that the advantages of each of the above approaches are not being fully exploited to test system hypotheses.

The present research project was designed to combine these three approaches in order to study the overall physical efficiencies of pasture-based dairy systems that differed in their season of calving. It was intended to use conventional analytical research to develop more appropriate methodologies which could, in turn, help to interpret and better understand the behaviour of the whole system while running a field experiment (experimental system research). Once this had been achieved, it followed that any 'simplified representation of the real systems' (i.e. models) could be either verified or, even better, validated using the experimental information that had been generated by the other two approaches.

The field experiment, which constitutes the "core" of the present thesis, was a whole farm systems study conducted at Massey University's No 1 dairy farm from

July 1996 to June 1999, in which the physical and economical performance of three contrasting calving systems (100% of cows calving in autumn (100A), 100% of cows calving in spring (100S), and 50% autumn calving-50% spring calving (50/50)) were investigated. However, in order to overcome the limitations imposed by the lack of appropriate standard methodologies for testing systems hypotheses, the research carried out involved a multi-approach program that included general systems studies, specific component studies, and modelling studies. The thesis is structured accordingly in three main parts.

2. Thesis outline

Part I (General Studies) contains three chapters. In Chapter 1, the literature is reviewed with regards to the effects of calving season and calving pattern on the main components and interactions of pastoral systems, with the focus on New Zealand conditions. In Chapter 2, the 3-year systems study is described in more detail, and the main physical results are discussed. In Chapter 3, the lactation curves of all cows in the three systems during the three years are studied in detail, including a comparison between the performance of linear and non-linear methods for the analysis of lactation curves.

The detailed component studies, together with some evaluations of methodologies, are presented in two chapters in Part II (Specific Studies). In order to be able to fully compare the performance and global efficiencies of the different calving systems, reliable estimates of the dry matter intakes by the cows are essential. Whilst several methods exist for estimating intakes of herbage dry matter on grazing cows, the estimation of individual intakes of both herbage and silage by grazing cows which are being offered the supplement as a group is much more difficult. Two short-term experiments were conducted to validate (indoor trial) and test (field trial) a combination of techniques for estimating herbage and maize silage intakes by in individual grazing cows supplemented as a group, and the results are presented in Chapter 4.

The three calving systems were managed by applying the same set of "grazing-management guidelines" (Chapter 2). Thus, a central interest in this thesis was to investigate the effects of applying such guidelines on the pasture growth curves, total pasture production, and herbage intakes by cows that had calved at different times of the year. This topic is covered in detail in Chapter 5, in which two methods for estimating herbage accumulation rates are compared. In addition, another three short-term experiments were conducted at different times of the year (September, December, and May) to estimate individual intakes of herbage dry matter on a relatively large number of cows from each system. Results from these trials are also outlined in Chapter 5, including a discussion about the performance of methods for estimating intakes of a herd or of individual cows. In addition, the methodology proposed in Chapter 4 was re-evaluated under different conditions and with a larger number of cows during the third short-term trial (May) in which the autumn-calved cows were being supplemented with maize silage. These results are also discussed in Chapter 5.

Chapters 6 and 7 of Part III cover the third and final approach of this thesis, Modelling Studies. Because systems research involves the application of management guidelines or decision rules (Macdonald and Penno, 1998), the integrated research objective of the present thesis needed a model which allows the simulation of applying different sets of management guidelines on a seasonal farm. Therefore, a dynamic, whole-farm model, was developed using a graphic programming interface. The model, which has been called IDFS (interactive dairy farm simulator), needs a decision-maker (i.e. the user) to make continuous decisions with regards to the allocation of cows in the paddocks, the use of supplementary feeds, and the conservation of forage, in a manner that is similar to the management methods used in actual systems experiments. The model is described in detail in Chapter 6, which includes an example of how the model is run and what outputs can be obtained. In Chapter 7, model predictions are compared with actual field experimental data, and three sets of "computer experiments" are used to exemplify the potential applicability of the model.

Finally, the thesis is completed by a General Discussion of the main results from each of the three parts, the methodological aspects of systems research, as well as the expected contributions of the present thesis to the understanding of dairy production systems and its conclusions.

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Part I

General Studies

Chapter 1

Effects of time of calving on the productivity of pasture-based dairy systems: A review

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Abstract. Effects of season of calving, date of calving within season and pattern of calving on different components of pasture-based systems of dairying and on the system as a whole are reviewed. Season and pattern of calving can influence the shape of the lactation curve (by influencing the level of yield at peak of lactation, the rate of decline after the peak, or the total days in milk), the annual milk yield and milk composition, the herd's reproductive performance and animal health. For systems in which the cows calve in spring with no imported supplementary feed, an earlier study reported small advantages from later calving, whereas more recent studies have shown advantages from earlier calving. These latter advantages resulted from extra days in milk, provided that sufficient feed was available for the herd in early lactation. A combination of early calving and extra feed in early lactation may achieve the benefits and avoid the disadvantages of early calving. Comparisons between autumn and spring calving systems showed that autumn-calved cows require more supplements during early lactation (winter) and usually have lower daily milk yields at peak lactation than spring-calved cows (spring). However, autumn-calved cows can have higher annual yields of milk and milksolids than spring-calved cows, mainly as a consequence of both longer lactations and higher daily milk yields during late lactation. Time of calving is a key element in construction of the farming system, which can be integrated with stocking rate, pasture supply, and availability of supplementary feed.

Keywords: calving season; pastoral; dairy systems; feeding management

1. Introduction

The season of calving (e.g., autumn or spring) and the distribution of calving dates (e.g., calving earlier or later within the spring season) within the herd have major effects on the herd's pattern of feed demand, and its supply of milk through the year. They are therefore major components of pasture-based dairy systems. The annual distribution of the milk supply is affected because lactation is a physiological process, which implies a rapid increase in milk yield from a relatively low value at calving up to a maximum level usually achieved around 5-6 weeks post-partum (Keown and Van Vleck 1973). This is followed by a gradual and variable decrease (or rate of persistency) in daily milk yield until the lactation is terminated, either naturally or selectively. In addition, changes in the availability and quality of feeds across the season can also influence the shape of the lactation curve and, consequently, the distribution of milk supply (Wood 1972).

In New Zealand, the majority of dairy cows calve in a concentrated pattern in late winter-early spring, which synchronises the increase in the herd's feeding requirements after calving with the increase in pasture growth during springtime (Holmes *et al*. 1987). Cows are therefore in late lactation during late summer-early autumn and are usually dried-off after relatively short lactations (220-240 days) in order to synchronise the low feed demand of the dry cows with the slow rates of pasture growth during winter. This common practice results in a very uneven distribution of the annual milk supply to the dairy factories, with about 130000 tonnes of milk fat plus milk protein processed in New Zealand during October 1997, but only about 1000 tonnes processed in June 1997 (Livestock Improvement Corporation 1998). The efficiency of the whole dairy industry might, therefore, benefit from a more even distribution of the annual milk supply.

Changes in time of calving include calving earlier or later within the spring season, as well as more drastic changes of the calving season (e.g., calving in autumn or in spring). However, because time of calving interacts with practically all the other components in the pastoral system including stocking rate, supplementation strategies and reproduction, its effects on the whole system cannot be considered in isolation.

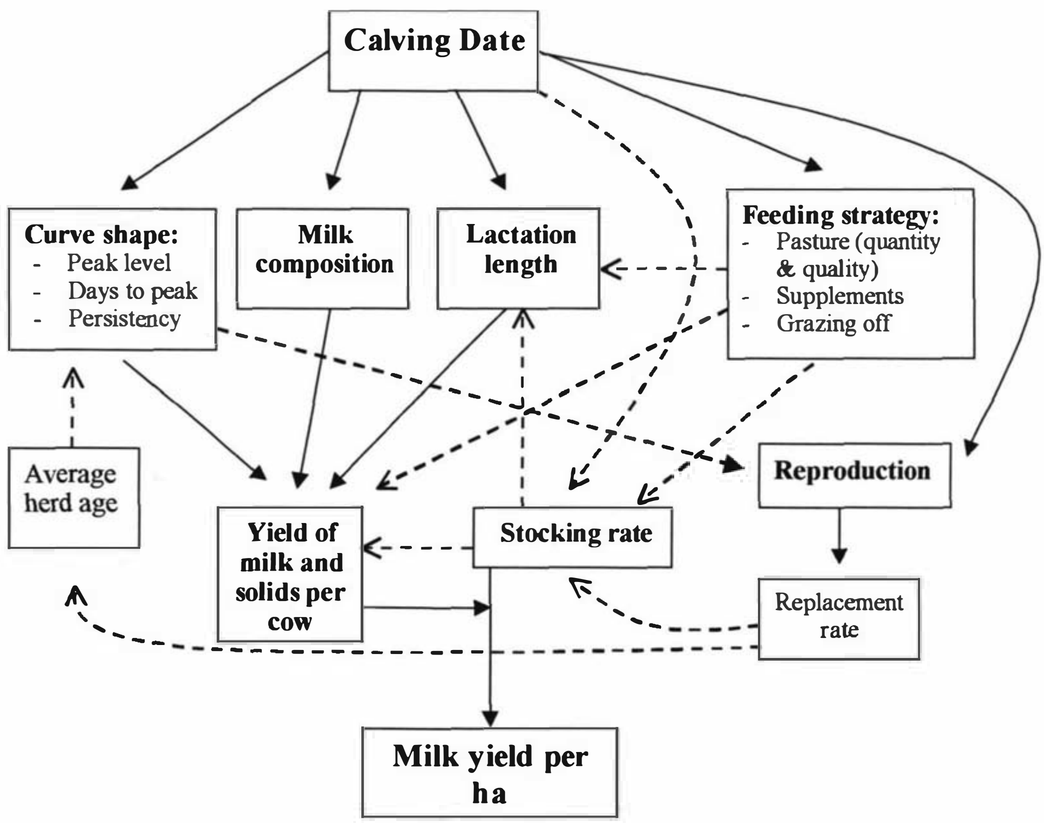
The present review discusses many of these factors and their interactions, with emphasis on New Zealand conditions. First, the effects of calving date (and calving season) on some major components of the dairy system are identified. Secondly, the relationships and interactions between calving date, calving season, calving pattern, and other major factors of pasture-based dairy farms, including stocking rate and supplementation, are discussed. Finally, the discussion focuses on the results of the small number of field experiments that have been designed to study the effects of calving season (autumn versus spring) on the whole system of production.

2. Calving date and pasture-based dairy systems

The season of calving may affect annual milk yield per cow and per ha in several direct and indirect ways. Changes include alterations to the shape of the lactation curve through changes either in the number of days between calving and peak yield, in the level of milk yield at peak and/or in the rate of decline in production after the peak (Keown *et al*. 1986); altering milk composition (Auldist *et al*. 1997a, 1998); and, influencing potential lactation length (Macmillan *et al*. 1984).

In addition, the feeding strategies used in pastoral-based dairy systems are likely to differ between herds in which the cows calve at different times of the year (García *et al.* 1998a). Different feeding strategies may result in significant changes in the lactation curve and, consequently, in the level of milk yield per cow. Furthermore, stocking rates may also differ according to differences in feeding strategies. These can result in an indirect effect of calving season on the milk production per unit area (Fig. 1).

Fig. 1. Possible direct (solid arrows) and indirect (broken arrows) ways in which calving date may affect total production per cow and per ha in a pasture-based dairy farm.



2.1. Calving date and the lactation curve

Studies in North America (Miller *et al.* 1970; Keown and Van Vleck 1973; Grossman *et al.* 1986; Keown *et al.* 1986), and in the United Kingdom (Wood 1972) have investigated the effects of calving date on the lactation curve. The common objective in these studies was to fit either linear (Miller *et al.* 1970; Keown and Van Vleck 1973) or non-linear models (Wood 1972; Grossman *et al.* 1986; Keown *et al.* 1986) to a variable number of individual and/or herd curves of lactation. In these models, calving date was included with several other factors (age, days in milk, lactation number, etc.) within herd or season.

2.1.1. Genetic and environmental factors.

The lactation curve is influenced by genetic and environmental factors (Dekkers *et al*. 1998). However, the shape of the curve, in terms of both the relative level of yield at the peak of lactation and the rate at which the milk yield decreases after the peak, depends greatly on environmental factors. Grossman *et al*. (1986) studied the effects of genetic and environmental factors on 397 first lactation cows. They fitted the data to a model similar to that proposed by Wood (1967) but modified it to account for seasonal variations other than season of calving. The lack of evidence supporting the genetic control of the lactation curve led the authors to conclude that "..there is little expectation for [genetic] selection to change the shape of the lactation curve..". This agrees with other studies in which lactation curves of similar shape have been reported for cows of different genetic merit (Keown *et al*. 1986; Dillon and Buckley 1998). However, Bar-Anan *et al*. (1985) have reported that persistency (defined as the average daily yield divided by peak yield) was relatively heritable (h^2 = 0.12 to 0.28) and that it was genetically and positively correlated with conception rate.

In the study by Grossman *et al*. (1986) the month of calving not only affected the shape of the curve, but also influenced the effects of season on the lactation curve. The environmental effects of the spring season were not the same for cows that had calved in autumn or in winter (Grossman *et al*. 1986). The environmental effects due to climate (such as temperature and humidity) can be separated into those effects that act directly on the animal and those that act through their feed (indirect effects). The direct effects are more marked in more extreme climates; for example, differences in temperature and photoperiod between seasons explained the effects of month of calving and birth on the total milk production of Holstein cows in Israel (Barash *et al*. 1996). This does not seem to be the case in temperate regions, nor in regions where cows graze on pasture for at least part of the year. In the UK, Wood (1972) compared the lactation curves of a traditionally managed herd (grazing in spring) with those from a herd fed indoors all year round. For the latter herd, month of calving had little effect on the persistency (defined as the extent to which peak production was maintained) or the week at which peak of production occurred (Wood 1972). Therefore, an indirect "feeding" effect was the principal component of the seasonal effects observed in the grazing herd, rather than a direct effect.

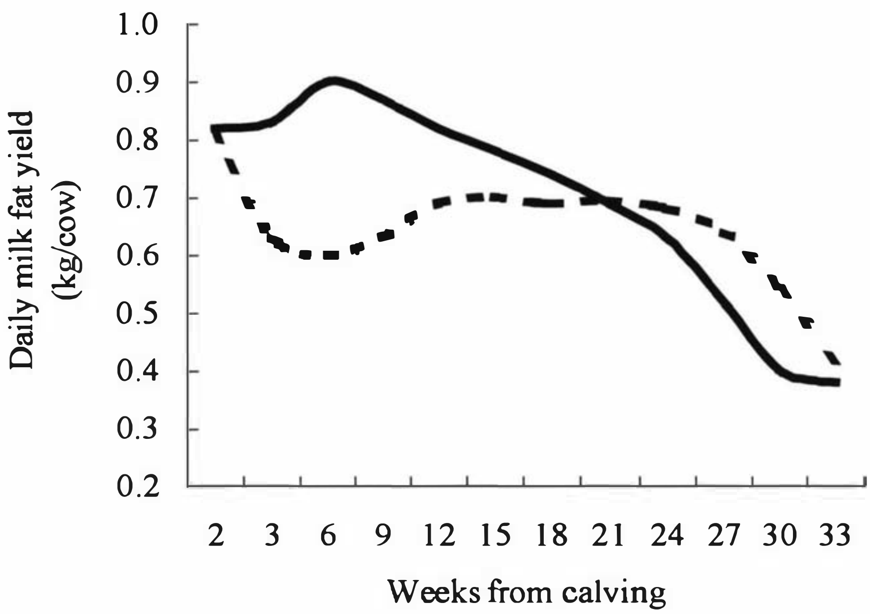
Keown *et al.* (1986) analysed a total of 270 lactation curves from herds of high and low production records and six seasons of calving. Their results showed that the differences in milk yield between the poorest and best months of calving were greater for low producing cows compared with high producing cows. The authors suggested that the high producing cows may have been kept under a higher degree of complete confinement resulting in a more uniform management throughout the year, whereas the low producing cows may have relied more heavily on pasture as a feed source (Keown *et al.* 1986) and were therefore affected more strongly by the seasonal effects. This agrees with the previous finding of Wood (1972).

2.1.2. Feed-related factors.

Herds which calved either early (mid July) or late (mid August) were compared on 8 pastoral farmlets in New Zealand during 3 consecutive years (Bryant 1982). Milk fat yield was similar for both groups of cows at the start of lactation, but early calving resulted in an underfeeding of the cows and, consequently, in very low daily milk yields during the first weeks of lactation. However, milk fat yield for these cows increased later in the spring and summer which, combined with longer lactations resulted in similar total lactation yields for both groups. The contrasting lactation curves (Fig. 2), and the fact that the early calving cows compensated for their lower daily yields in early lactation with higher persistency and more days in milk, demonstrate the "flexibility" of the cow and the lactation curve in responding to enforced changes in the pattern of feed supply.

More recent studies in New Zealand by Auldist *et al.* (1997b) and García *et al.* (1998a, 1998b) and in Ireland by Ryan *et al.* (1997) have shown significant differences in the shape of lactation curves between autumn- and spring-calved cows. Cows calved during autumn had a lower level of milk yield at the peak but higher persistency rates. Moreover, two studies reported a "second" peak of lactation for the autumn-calved cows during the following spring, a result that was associated in both cases with a greater availability and quality of pasture in spring (Auldist *et al.* 1997b; García *et al.* 1998a, 1998b). Thus, the higher availability and quality of pasture during the spring can strongly affect the shape of the lactation curve in pasture-based systems. This also supports the observations of Wood (1972), who demonstrated that the seasonal effects of the spring on the shape of the lactation curves were due to the "flush" of pasture during that season and the consequent increase in feeding level.

Fig. 2. Lactation curves (average for three years) from cows that had calved early (broken line) or late (solid line) in the spring season. (Redrawn from Bryant 1982).



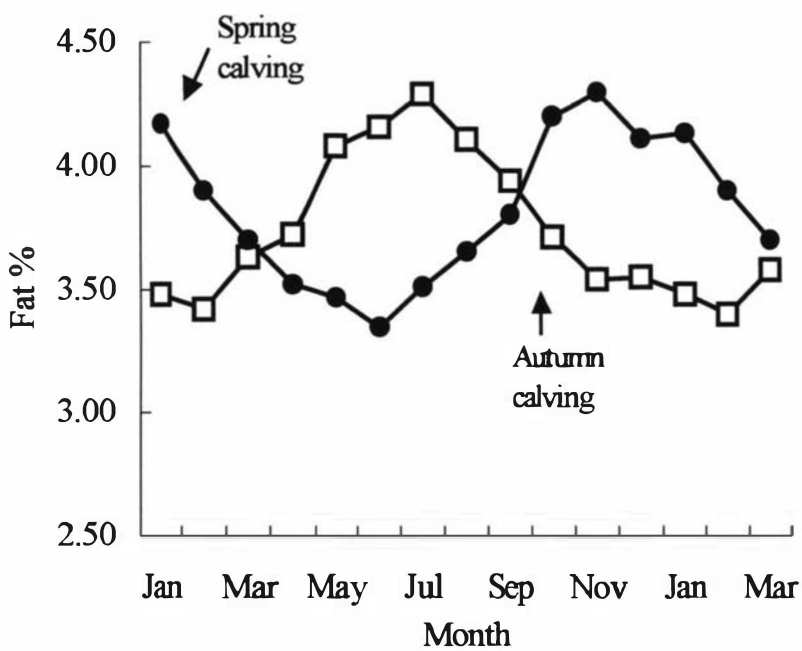
2.2. Calving date and milk composition

Both stage of lactation (SOL) and time of the year can affect milk composition (Kennelly 1996). The concentrations of protein and fat follow a curve that is generally the inverse shape of the lactation curve for milk yield, decreasing from calving to a minimum at peak of lactation and increasing again during late lactation, whereas the concentration of lactose in mid lactation is relatively constant (Holmes *et al.* 1987).

The effects of SOL include changes in both the major (e.g., increased milk fat concentration in later lactation) and minor components (e.g., proportions of long-chain and short-chain fatty acids) of milk (Kennelly 1996). Consequently, a change in calving date can significantly influence the average composition of the milk supplied to the factory at a particular time, as illustrated for fat concentration in Fig. 3 (Dillon and Crosse 1997) and, consequently, the processing characteristics of the milk (O'Brien *et al.* 1997).

The season of the year may also influence milk composition by means of direct effects on the animal (temperature, humidity, and photoperiod) or indirectly through changes in pasture quantity and quality. In New Zealand, where about 95% of the cows calve during late winter-early spring, the effects of the stage of lactation and time of the year are confounded. A recent study by Auldist *et al.* (1998) in New Zealand was designed to separate and quantify these two effects using four herds (20 cows each) which calved in either summer (January), autumn (April), winter (July), or spring (October).

Fig. 3. Seasonality of fat content from cows which calved in autumn (September/October, □—□) or in spring (February/March, •—•) in Ireland (Redrawn from Dillon & Crosse 1997).



Season of the year and SOL both had significant effects on the milk composition (Table 1), although the overall effects of the former were quantitatively greater than the effects of SOL. Concentrations of fat and protein were higher in late lactation than in early lactation and also highest during winter. In addition, the difference in the concentration of protein and fat between early and late lactation was greater in winter than in summer, which resulted in a significant interaction between season and SOL. However, ratios of casein:whey protein and protein:fat, which influence the processing characteristics of milk, were affected by time of the year but not by SOL (Auldist *et al.* 1998).

Table 1. Effects of season of the year and stage of lactation (SOL) on milk production and composition, from Auldist *et al.* (1998). EL, early lactation; ML, mid lactation; LL, late lactation; S, stage of lactation; T, time of the year (season); NS, not significant; *, $P < 0.05$; **, $P < 0.01$.

	Spring			Summer			Autumn			Winter			Main effects		
	EL	ML	LL	EL	ML	LL	EL	ML	LL	EL	ML	LL	S	T	SxT
Milk yield (kg d^{-1})	18.5	14.3	11.7	20.4	17.4	13.6	19.6	14.8	12.8	19.0	12.3	8.9	**	**	*
Fat (g kg^{-1})	42.2	45.3	46.3	42.0	44.4	48.3	42.1	49.8	49.7	44.5	50.1	53.2	**	**	NS
Protein (g kg^{-1})	29.7	30.7	33.0	29.9	32.7	33.7	28.9	32.7	34.0	28.7	33.6	34.9	**	*	*
Lactose (g kg^{-1})	49.4	49.2	47.8	48.9	49.9	49.0	49.2	47.5	49.3	48.1	46.4	44.9	**	**	**

2.3. Calving date and reproductive performance

2.3.1. Direct and indirect effects

Calving date may directly influence the reproductive performance of a herd through differences in the environmental conditions at the time when cows are expected to conceive (Mercier and Salisbury 1947). This can be particularly important in dairy systems with all year round calving patterns, as is the case in some districts of Australia (see Ashwood 1985). In a feedlot dairy in Queensland, the interval between calving and first ovulation was significantly longer in cows which calved in late spring and summer than in those which calved in late autumn and winter (Jonsson *et al.* 1997a). The average calving rate (defined as the proportion of services that resulted in a subsequent calving) in 58 commercial farms in Ireland decreased from around 60% for cows that had calved in January and were mated in the spring, to around 40% in cows which had calved in April-June and were mated during the summer (O'Farrell *et al.* 1997).

The season of calving may also interact with fertility in some indirect ways (Fig. 1). For example, if fertility is impaired because the cows are mated during unfavourable climatic conditions, the replacement rate is likely to be higher, with the greater number of first lactation animals having adverse effects on the overall results of the next breeding season (McDougall 1993; Grosshans *et al.* 1997). The overall supply of milk can also be affected due to the consistently lower level of milk yields and flatter lactation curves that have been reported for first lactation cows (e.g., Bar-Anan and Genizi 1981; Keown *et al.* 1986).

2.3.2. Autumn versus spring calving

In temperate regions like New Zealand, Victoria, and Tasmania, autumn calving inevitably means that the mating period occurs during winter. Whether this fact affects the reproductive performance of grazing cows in temperate regions is still uncertain. An early study involving over 12000 lactation records from New Zealand farms in which some cows calved in autumn and some in spring, reported slight advantages in reproductive performance for the spring-calved cows (Shrestha 1978). Similarly, survey data collected by Fulkerson and Dickens (1985a) comprising 2593 cows in 30 herds in Australia and by Chang'endo (1996) in New Zealand (3787 cows in 8 farms) indicated a lower breeding performance for autumn-calved cows than for their spring counterparts (Table 2).

Table 2. Reproductive performance of cows calving in spring and autumn, from Fulkerson & Dickens (1985a, 1985b), Fulkerson *et al.* 1987, Chang'endo 1996. ND, data not reported; *, submission rate after 28 days; non-return rate after 42 days. **, within each column, values are statistically different ($P < 0.05$) between autumn and spring calving seasons.

Source	Time of calving	Submission rate after 24 days (%)	Non return rate in the following 21 days (%)	Estimated true non-return rate (%)	Conception rate (%)	N°of empty cows
Survey (Fulkerson & Dickens 1985a, 1985b)	Spring	87	72	68	ND	ND
	Autumn	75	55	40	ND	ND
Survey * (Chang'endo 1996) **	Spring	81	63	ND	ND	10
	Autumn	77	57	ND	ND	12
Systems comparison (Fulkerson et al. 1987)	Spring	87	68	ND	64	3
	Autumn	90	62	ND	53	5

The lower breeding performance of the autumn-calved cows in Australia was not due to differences in average body condition score, age, milk fat yield, or a longer interval between calving and mating as all these variables were similar for both groups (Fulkerson and Dickens 1985a, 1985b). The combined survey data in Table 2 suggest a double effect of both an impaired heat detection (lower submission rates) and also a lower conception rate (lower non-return rates) for the autumn-calving cows. Although the reasons for these differences are not obvious, Fulkerson and Dickens (1985b) have postulated a combination of different factors including the physiological effect of daylength or ambient temperature, differences in energy balance associated with management practices, and inclement weather during winter. The second factor was probably the most important, as cows mated in late spring were gaining weight at mating whereas cows mated in winter were either losing, or maintaining weight (Fulkerson and Dickens 1985b).

In a four-year comparison of autumn versus spring calving systems, Fulkerson *et al.* (1987) also reported lower conception rates and higher non-pregnant rates for the autumn-calved cows (Table 2). The high submission rates for both herds after 24 days of the breeding period suggests that heat detection was not the main factor responsible for the lower performance. This may partially explain the higher submission rates observed for autumn calving cows in the systems study than in the survey of farms, because oestrus was detected by observation at milking time and aided by use of hormone-treated steers in the former (Fulkerson *et al.* 1987).

In contrast to the results of Fulkerson and Dickens (1985a, 1985b), Fulkerson *et al.* (1987), and Chang'endo (1996), no unequivocal evidence for a lower reproductive performance by autumn-calving cows has been reported in other whole-farm comparisons of autumn versus spring calving systems (Thomas *et al.* 1985; García *et al.* 1998a, 1998b). It should be noted that the systems study by Fulkerson *et al.* (1987) was intended to evaluate the productivity of autumn and spring calving under a management system that fully utilised only farm grown feed as pasture. Therefore, the autumn-calved cows were underfed during the first 3 months after calving, receiving an average of 2.6 kg DM grazed pasture plus 7.2 kg DM grass silage per day.

2.3.3. Peaks of lactation, persistency, and fertility

Autumn-calved cows in temperate regions peak at a lower daily yield than spring-calved cows but have shown higher persistency rates (Ryan *et al.* 1997; García *et al.* 1998a, 1998b), which could theoretically influence the level of fertility. In fact, high lactation yields from dairy cows which have comparatively lower milk yields at peak of lactation, but greater persistency rates are less antagonistic to fertility (Bar-Anan *et al.* 1985), in association with a smaller negative energy balance (NEB) in the cows. However, while the NEB is correlated with the level of peak production, it does not depend strictly on the latter (Macmillan *et al.* 1996). In pasture-based systems, for instance, the NEB can be even greater for low-producing cows which fail to satisfy their potential intakes under competitive grazing conditions (Macmillan *et al.* 1996). This concurs with results of McDougall *et al.* (1995), who reported a positive relationship between daily milk yields and conception rates to the first service for cows fed pasture alone, or pasture supplemented with grass silage. In addition, a survey involving almost 3000 cows in 26 commercial dairy farms in Tasmania (pasture-based systems) showed a positive rather than a negative relationship between milk production and reproduction (Fulkerson 1985). Even for cows which were producing in excess of 1 kg milk fat per day, reproduction was affected only when the condition score 3 weeks after calving was low (≤ 4). It is probable that, in these cases, high milk yields indicated also high intake levels, low NEB and, consequently, high fertility.

Thus, even though the negative association between high genetic merit (O'Farrell *et al.* 1997; Jonsson *et al.* 1997b; Mayne 1998) or high peak yield (Bar-Anan *et al.* 1985; Lean *et al.* 1989; Macmillan *et al.* 1996) and fertility cannot be ignored, its importance under pastoral conditions is less certain. This is, firstly, because some of these results were obtained from very high producing cows in Israel (Bar-Anan *et al.* 1985) and California (Lean *et al.* 1989) under systems of production which are very different from pastoral systems. Secondly, it is because New Zealand cows are sometimes restricted in intake at peak of lactation but can still achieve comparatively high conception rates (60 to 65%) at first insemination (Macmillan *et al.* 1996). For pasture based-systems, therefore, the extent to which the NEB is related either to lower intakes or to high yields and moderate intakes, is still unclear.

2.4. Calving date and animal health

There is little evidence of direct effects of calving date on animal health. However, metabolic problems are more likely to occur around peak of lactation (Dekkers *et al.* 1998; Knight 1998) than at any other time of the year, probably independently of the calving season. Consequently, Knight (1998) has questioned the traditional dairy system that requires an interval of 12 months between consecutive calvings, and high daily milk yields at the peak of lactation. It may be possible to extend the duration of lactation up to 18 months with the consequent reduction in the probability of the risks associated with calving and the peak of lactation.

In pasture-based systems, calving date may have an indirect effect through changes in the mineral composition of pasture. The incidence of two of the main metabolic diseases in New Zealand (hypocalcemia and hypomagnesemia) is likely to be higher for spring rather than autumn-calved cows owing to greater mineral deficiencies and/or imbalances with respect to Ca and Mg in spring pasture (G. Wilson, unpubl. data). However, preliminary results from a comparison between autumn and spring calving systems have not shown unequivocal evidence to support the hypothesis (S. C. García, unpubl. data).

As noted above, in temperate regions like New Zealand, autumn-calving cows have shown a higher persistency of lactation and also higher levels of milk yield during late lactation (García *et al.* 1998a, 1998b). Higher milk yields at the end of lactation are normally associated with lower somatic cell counts, probably as a result of a dilution effect (Lacy-Hulbert *et al.* 1995). In contrast, spring-calved cows have lower milk yields in late lactation usually with higher somatic cell counts. Whether these facts may translate into different levels of mastitis incidence is still unknown.

3. Calving date and interactions with other major components of the pastoral systems

3.1. Calving date, calving pattern, and stocking rate

In New Zealand, the studies involving calving date or calving season have concentrated either on the comparison of early versus late calving during the late winter-early spring season (Hutton 1967, 1968; Hutton and Parker 1967; Campbell 1968; Bryant 1982; Macmillan *et al.* 1984), the effects of calving spread (Macmillan *et al.* 1984), the relationship between peak yield and calving date (Paul 1982; Macmillan *et al.* 1984), the interactions between calving date and stocking rate (Campbell 1968; Bryant 1982), the effects of calving date on milk composition (Auldist *et al.* 1998), or the comparison between autumn and spring calving systems (García *et al.* 1998a, 1998b). Results from some of these studies have been previously summarised by Holmes and Macmillan (1982) and by Simmonds (1985).

Hutton (1967, 1968) and Hutton and Parker (1967) compared early (26 July) and late (2 September) mean calving dates at a high stocking rate (4.94 cows ha^{-1}). An average of 232 kg of meal per cow was fed to both herds. Calving later resulted in 5% increase in the milk fat yield per ha averaged over three years. Later calving was also associated with a greater availability of pasture on the farm around calving time, which in turn resulted in a higher daily milk fat yield (by 15% to 20%) in early lactation. Although daily yield decreased more rapidly for the late calving cows, the difference in milk yield persisted sufficiently to offset the effects of approximately 20 extra days in milk achieved by the early calving cows. These results had a major impact on the farming community and a rapid trend towards later calving date in spring occurred in the following years (Bryant 1989). In spite of the consequences of these investigations, two aspects in Hutton's (1967, 1968) experiments are worthy of further consideration.

First, the 5% higher milk fat yield per cow (and per ha) from later calving was the average of 0.7%, 9.0%, and 3.5% for 1965/66, 1966/67, and 1967/68 seasons, respectively, showing that the difference between the two systems was very small in two out of the three years. This is particularly important for trials involving non-replicated farmlets, as was the case in Hutton's (1967, 1968) experiments.

Secondly, if the higher level of milk yield at peak was mainly due to a better feeding level of pasture at calving time, then this difference should disappear if sufficient feed could be provided by means of either grazing management during the previous winter, or by the use of supplements. Provision of extra pasture was studied by Bryant and Cook (1980), Bryant and MacDonald (1983), and Bryant and L'Huillier (1986), who demonstrated that the amount of pasture at calving time (late winter-early spring) can be manipulated by different grazing management strategies during autumn and winter, with significant positive relationships between the amount of pasture and the total milk fat yield per cow from calving to 31 December. Similarly, extra pasture can be provided by the application of nitrogen fertiliser during winter, in order to meet the needs of early calved cows (Thomson *et al.* 1991).

Major efforts were made in Hutton's (1967, 1968) experiments to ensure that the total quantities of concentrate fed in each season were similar for both treatments although the pattern of feeding was somewhat different. Even though this objective was achieved in each of the three seasons, there is little evidence in the published results to show that the earlier calving cows did actually receive the amount of concentrate that they required to offset the deficit in pasture availability. In fact, average data of four consecutive years of the same trial presented by Parker (1969) indicated that the early calving cows averaged a meal consumption of only 0.9, 2.3, and 1.2 kg (as offered) of concentrate per cow per day for August, September, and October, respectively. The corresponding figures for the late calving group were, respectively, 0, 0.9, and 1.8 kg per cow per day.

In some countries, where the cows must be wintered indoors for climatic reasons, additional feeding will require the use of additional supplements, as reported by Dillon *et al.* (1995) from a whole farm comparison between early (late winter) and late (early spring) calving dates that was carried out over three years in Ireland. Cows were stocked at 2.9 cows ha^{-1} and the difference between the mean calving dates of the early and late groups was 51 days, greater than in all the previous New Zealand studies outlined above. A summary of the main results is shown in Table 3.

Table 3. Summarised results of the effects of early and late calving dates and different stocking rates in Ireland, from Dillon *et al.* 1995.

Item	Early calving 2.9 cows ha^{-1}	Late calving 2.9 cows ha^{-1}	Late calving 2.6 cows ha^{-1}
Milk yield (kg)	5872	5444	5584
Milk fat + protein (kg per cow)	397	388	404
Milk fat + protein (kg ha^{-1})	1151	1123	1049
Concentrates offered (kg DM per cow)	558	167	72
Silage conserved (t DM ha^{-1})	4.3	4.2	4.7
Lactation length (days)	307	304	310

Later calving significantly decreased the milk yield but increased the concentration of milk fat and milk protein. Consequently, milksolids yields per cow and per ha were similar ($P > 0.05$) for both calving dates. The main effects on milk composition occurred during the first 6 to 7 weeks of lactation. The early calving herd had a lower average concentration of protein (28 g kg^{-1}) at peak of lactation than that of the later calving herds (32-33 g kg^{-1}), an effect that was attributed to differences in the feeding strategy. Early calving cows were kept indoors after calving and received grass silage plus a relatively higher amount of concentrates, in contrast to later calving cows which grazed pasture after calving and were supplemented with a lower amount of concentrates (Dillon *et al.* 1995). Thus, an additional 0.43 t of concentrate DM per cow was necessary in this experiment to meet the feed demands of the early calving systems, in order to achieve a level of milksolids per ha which was similar to that of the later calving systems.

The relationships between calving date, the amount of feed on the farm, and the use of supplements are important in this context. In an experiment in which no supplements were fed, so that the early-calved cows were underfed in early lactation, Bryant (1982) found that later calving dates (14 August) resulted in slightly more milk fat yield per ha (+2.9%) than early calving dates (21 July), particularly at a high stocking rate (4.32 cows ha^{-1}). These results concur with those of a survey of 554 farms in the Waitoa region (New Zealand) conducted by Paul

(1982), who compared daily milk fat yield at peak of lactation with the total lactation yield for cows that calved between 1 July (early) and 20 August (late). Although no differences were found in the total milk fat production per cow, calving later was associated with higher daily milk fat yields at the peak of lactation, reflecting higher feeding levels in early lactation for the later calving cows (Paul 1982).

However, other earlier (Campbell 1968) and more recent studies (Macmillan *et al.* 1984) have found a higher total production per cow and per ha for cows that had calved early rather late in the season. Campbell (1968) compared the effect of early (1 August) or late (13 September) calving dates at two stocking rates (3.1 versus 4.3 cows ha^{-1}) and reported an increase in milk fat yield per ha of 15% and 25% for the earlier calving herds at each of the stocking rates, respectively. The relatively large effects were mainly due to longer lactation lengths for the early calving cows, as both herds were dried-off on the same day in April, and may reflect the fact that 13 September is actually very late.

Macmillan *et al.* (1984) evaluated the performance of the two members of pairs of identical twins which differed within pairs by 30 days in their mean calving date (July versus August), and were grazed together after calving. An interesting feature of this experiment was that both the early calving and late calving groups had very concentrated calving periods (35 days), so that confusion between calving date and calving pattern was avoided. Earlier calved cows produced 22 kg more of milk fat in the whole lactation, an effect associated with a longer (37 d) lactation length.

In the same comparison, Macmillan *et al.* (1984) also studied the effects of similar mean calving dates but different calving patterns in terms of spread. A more concentrated calving pattern also resulted in a higher level of milk fat yield per cow due to longer lactation lengths. When compared with averaged data of 35 commercial farms from the same region, the combined results of early calving and a more concentrated calving pattern in the research station translated into 29 more days in milk (21 and 7 days for each of the effects, respectively; Macmillan *et al.* 1984). It is important to note that concentrated calving periods are achieved in New Zealand with the some assistance from premature calving induced in about 12% of the herd, a practice associated with longer lactations but also with a reduction of daily milk yield over the entire lactation (Hayes *et al.* 1998).

Thus, despite earlier information indicating small advantages for calving relatively later, more recent research suggests that a relatively earlier calving date and a more concentrated calving pattern will result in a higher level of milk fat yield per cow, but only if the lactation length is actually extended. However, this potential advantage may disappear if an early mean calving date results in severe underfeeding of the cows in early lactation.

If an adequate feeding level can be provided to the cows in early lactation either as sufficient pasture, or as supplements, an additional advantage of a relatively earlier mean calving date is that the majority of the milk will be produced during spring and early summer. This effect can be important in some areas of New Zealand in which the variability between years in terms of pasture production increases significantly during summer and early autumn (Thomson 1998).

3.2. Supplements for early or late lactation

With a national average lactation length of 223 days (Livestock Improvement Corporation 1997) and a system which is restricted to calve in 12-month cycles, it is clear that any factor that can extend the days in milk will have a major impact on the New Zealand farm's physical level of production. Indeed, supplements have been shown to produce larger responses when fed in late rather than early lactation (Clark 1993; Penno *et al.* 1995; Pinares and Holmes 1996). This is not because the physiological response (or immediate response) of the cows is higher in late lactation, but simply because the main effect of the use of supplements in this case is to extend the lactation length. However, the immediate response to supplementary feed would theoretically be expected to be higher in early rather than in late lactation, for two reasons. First, the ability of a cow to partition nutrients towards the mammary gland is at its maximum during early lactation, when the physiological control of the lactation is under the highest expression of homeorhetic control (Bauman and Currie 1980; Vernon 1998). Secondly, the main effect of supplements when they are fed with restricted pasture allowances, is to increase the total DM intake and probably the total nutrient intake also, because the substitution rate (kg pasture DM not eaten per kg of extra supplement DM eaten) usually varies between 0.24 and 0.45 kg kg^{-1} under these conditions (Stockdale *et al.* 1997).

Therefore, if high quality supplements could be used to obtain better individual responses in very early-calved cows, a double beneficial effect could be obtained in a dairy herd in terms of production. First, a higher immediate response in terms of kg of milk per kg of supplement DM would be expected, and, secondly, lactation length could be extended with less difficulty by calving the cows earlier in the season, so that more milk could be produced before the period of maximum variability in pasture quantity and quality (late summer and early autumn). While these effects are currently being evaluated at Waimate West in New Zealand (K. Davies, unpubl. data), the whole farm comparison between autumn and spring calving systems described earlier (García *et al.* 1998a, 1998b) can be used to illustrate this point.

Autumn calving can be seen as the extreme situation of "early" calving dates. The use of high quality supplements in early lactation is crucial for autumn calving cows, and their lactation lengths can easily be extended to nearly 300 days without the use of supplements in late lactation (García *et al.* 1998a, 1998b). Supplements were used in this case primarily to compensate for the limited quantity of available pasture to the cows in early lactation (winter). Nevertheless, daily milk yield at peak of lactation was lower for the autumn-calving cows than for the spring calving cows in that experiment and in other similar systems comparisons (see below). While this suggests the need of further research in the use of supplements for autumn-calved cows in early lactation, even if it were possible to fully feed cows on pasture in winter (e.g., with a low stocking rate), daily peak milk yield would be expected to be lower than for spring-calved cows, because of differences in the chemical composition of pastures (Suksombat *et al.* 1994).

4. Whole farm comparisons of autumn versus spring calving systems

A summary of the four studies which have compared autumn versus spring calving systems using farmlets or whole farms is presented in Table 4. All these comparisons were carried out in temperate regions, two of them in Australia (Thomas *et al.* (1985) in Victoria and Fulkerson *et al.* (1987) in Tasmania), one in Ireland (Ryan *et al.* 1997, 1998), and one, which is continuing, in New Zealand, (García *et al.* 1998a, 1998b). Other work in the UK (Hameleers and Roberts 1992) has also compared autumn and spring calving cows in a whole system study but with the main objective of evaluating "tight" as opposed to "normal" grazing during the spring. Although it is difficult to draw general conclusions because of differences between experiments (e.g., in terms of regions, levels of pasture production, stocking rates, and use of supplements), several important points arise from an analysis of Table 4. First, with the exception of the study by Fulkerson *et al.* (1987), autumn-calved cows produced between 9-17% more milk fat per cow than spring-calved cows. Secondly, milk fat yield per ha was higher (also from 9 to

17%) for the autumn calving systems in those two studies in which stocking rates were the same for autumn and spring calving systems. Milk fat yield per ha, however, was lower for the autumn calving systems in the other two studies, in which the autumn calving cows were stocked at lower rates. Thirdly, in all four experiments, a larger amount of supplements was fed (range between 42 and 122% more supplements) and a larger area was conserved (range between 21 to 160% more area) for the autumn-calving systems than for the spring-calving systems.

Table 4. Whole farm or farmlet comparisons of autumn and spring calving systems. ND, data not reported.

Item	100% Autumn	100% Spring Early	100% Spring Late	50% Aut: 50% Spr	Reference
Stocking rate (cows ha^{-1})	2.0	2.0	2.0		Thomas et al. 1985
Supplements fed (t per cow)					
Concentrates	0.4	-	-		
Roughage (hay and/or silage)	1.0	0.63	0.8		Average results of 2 years
Area conserved (% of total farm)	100	40	50-65	Not compared	
Milk fat					
Kg per cow	214	183	183		
Relative to spring calving (%)	+17	-	0		
Kg ha^{-1}	428	366	366		
Relative to spring calving (%)	+17	-	0		
Stocking rate (cows ha^{-1})	2.56	2.56		2.56	Ryan et al. 1997
Supplements fed (t per cow)					
Concentrates	1.5	0.66		1.1	
Roughage (hay and/or silage)	ND	ND			Results of 1 year
Area conserved (% of total farm)	100	74		71	
Milk fat					
Kg per cow	269	247		268	
Relative to spring calving (%)	+9	-		+8.5	
Kg ha^{-1}	689	632		686	
Relative to spring calving (%)	+9	-		+8.5	
Stocking rate (cows ha^{-1})	1.45	1.6			Fulkerson et al. 1987
Supplements fed (t per cow)					
Concentrates	0	0			
Roughage (hay and/or silage)	1.68	1.18			Average results of 4 years
Area conserved (% of total farm)	62	51		Not compared	
Milk fat					
Kg per cow	157	164			
Relative to spring calving (%)	-4.3	-			
Kg ha^{-1}	260	304			
Relative to spring calving (%)	-14.5	-			
Stocking rate (cows ha^{-1})	2.0	2.4		2.1	García et al. 1998a, 1998b and unpublished data.
Supplements fed (t per cow)					
Concentrates	0	0		0	
Roughage (hay and/or silage)	1.12	0.63		0.84	
Area conserved (% of total farm)	73	28		49	
Milk fat					
Kg per cow	211	186		202	Average results of 2 years
Relative to spring calving (%)	+13.4	-		+8.6	
Kg ha^{-1}	422	441		422	
Relative to spring calving (%)	-4.3	-		-4.3	

The only experiment in which autumn-calved cows produced less (4.3 %) milk fat per cow (Fulkerson *et al.* 1987) was also the one in which only supplements made on the farm were used. In addition, the amount of supplements fed to the cows and the area conserved (both expressed as a ratio relative to the spring systems) were the lowest of the four experiments (Table 5). Moreover, the autumn-calved cows in that trial received an average of only 2.6 kg DM per cow of pasture during the first 3 months of lactation. In spite of the *ad lib* access to good quality silage, total daily DM intake averaged only 9.8 kg DM per cow during the same period; this was reflected in the low daily milk fat yield at peak of lactation, which was around 0.80 kg per cow for the autumn-calved cows in contrast to 1.05-1.10 kg per cow for the spring-calved cows (Fulkerson *et al.* 1987). In the other two experiments for which the lactation curves are presented, daily peak yield was also lower for the autumn-calved cows than for their spring counterparts. However, in those two studies there was no evidence to show that the autumn-calved cows were fed on a low feeding level during early lactation (Ryan *et al.* 1997; García *et al.* 1998a).

Table 5. Ratios (value for autumn system:value for spring system) for the total amount of supplements fed and area conserved.

	Thomas et al. 1985	Ryan et al. 1997	Fulkerson et al. 1987	García et al. 1998a, 1998b
Total supplements fed/cow	2.22	2.27	1.42	1.77
Total area conserved	2.50	1.35	1.21	2.60

The higher total milk fat yield for the autumn-calved cows in the studies of Ryan *et al.* (1997) and García *et al.* (1998a, 1998b) was entirely due to a higher daily yield in late lactation in the former study, but was due to a combination of a higher yield in late lactation plus longer (+ 41 days) lactations in the latter study. This occurred despite the fact that in both experiments, spring-calved cows produced about 2 litres per cow higher daily peak yields than the autumn-calved cows. Lactation length was also longer (± 20 days) for the autumn-calved cows in the study of Fulkerson *et al.* (1987), although this was not sufficient to compensate for the severe underfeeding and low daily yields of the autumn-calved cows during early lactation.

These results concur with those of a survey of eight commercial winter milk producing dairy farms in Palmerston North, New Zealand (Chang'endo 1996). On each, the autumn-calved cows produced more milksolids (+3.6%), because of greater lactation lengths (+24 days) than their spring counterparts and despite lower daily milk yields at peak of lactation.

Thus, the evidence presented here suggests that 100% autumn-calving systems can produce similar quantities of milksolids per ha to those produced by 100% spring-calving systems. It is also evident that a larger amount of supplements would be required for a 100% autumn-calving system, ranging from 0.5 to 0.85 t DM extra per cow in the four experiments summarised here. However, García *et al.* (1998b) reported a relatively high contribution of grazed pasture to the total annual diet for the autumn- (80%) and spring-calved cows (90%). The difference between the two systems was even smaller (80 vs. 83%, respectively) during the second year of the trial because the spring-calved cows required higher amounts of supplements during the dry summer in this year (S. C. García, unpubl. data).

Season of calving may also interact with genetic merit. In pasture-based systems, cows of higher breeding index have been shown to produce more milk than cows of lower breeding index (Bryant 1981; Grainger *et al.* 1985). However, high genetic merit cows were also dried-off with lower body condition score, as these cows divert a higher proportion of their nutrient intakes to milk production and a lower proportion to live-weight gain (Grainger *et al.* 1985). In other words, this could mean that spring-calving cows of higher breeding index would be dried off earlier than cows of lower breeding index if pasture supply diminishes in late summer early autumn. Therefore, high genetic merit cows calving in autumn rather than in spring could, theoretically, have better individual responses to supplementary feed in early lactation (winter) and, at the same time, they could have a lower risk of being affected by a low level of feed supply in late lactation.

A potential advantage of the autumn-calving herds is related to the practical perception that grazing pressure during spring can be higher for those cows. In this sense, it seems reasonable to think that a given value for post-grazing residual herbage mass (e.g., 1500 kg DM ha^{-1}) would be more readily achievable in springtime without affecting individual milk yields with autumn-calved cows rather than with spring-calved cows, which are in early lactation at that time of the year. The concept of course does not imply a significant restriction in the pasture offered, in which case the cows' yields would be affected regardless of whether they are in early or late lactation (Holmes *et al.* 1985).

In practice, this would allow the application of a "tighter" grazing management (higher grazing pressure) for autumn-calved cows during spring with two important consequences. First, surpluses can be easily identified and a larger area can be harvested earlier in the season (Roberts *et al.* 1993). Secondly, better pasture quality during the following summer as a result of the intense spring grazing could result in higher levels of milk yield later in the season, particularly for split calving systems (autumn and spring) where the better quality pasture can be then allocated to the early lactation, spring-calved cows. This effect has been demonstrated under both rotational (Mitchell and Fulkerson 1987; Stakelum and Dillon 1990) and continuous grazing (Roberts *et al.* 1993).

In contrast to this view, late control (lower grazing pressure during early spring followed by a period of high grazing pressure during anthesis) rather than early control (more severe grazing management during early spring) has been proposed in New Zealand in order to achieve higher pasture DM production in the following summer-autumn. While this theory has been proved under controlled experiments and by component research (Da Silva *et al.* 1993), a large scale experiment failed to demonstrate any advantage in terms of milk production (Bishop-Hurley *et al.* 1997).

5. Summary and implications

This review has illustrated how calving date, season of calving, and calving pattern all play major roles in the productivity of a pasture-based dairy farm. It is clear that these three components influence the level of milk yield at the peak of lactation and persistency, effects that in turn will be reflected in the shape and duration of the lactation curve. Because of these effects, it is also clear that any attempt by the New Zealand dairy industry to overcome the problem of the "spring flush" of milk must consider changes in the calving date and/or calving season.

The information reviewed here highlights three important points. First, despite the similar productivity between systems in which the cows calve earlier or later in the spring season, early calving has been shown to be consistently associated with the achievement of longer lactation lengths. It was suggested that the combination of very early calving dates with an allocation of supplements in early lactation could result in the double benefit of a higher immediate response by the cow, plus longer lactations without the need of supplementary feed in late lactation.

Secondly, autumn-calving systems plus extra supplementary feed are able to produce similar total yields to those produced by traditional, spring-calving systems. A key factor in achieving this is that lactation of autumn-calved cows can be extended easily to nearly 300 days in pastoral systems. Indeed, the main reason for drying-off autumn-calved cows is usually to allow for a dry period of at least 60 days before the next calving. Spring-calved cows on the other hand, are usually dried-off because their condition score is low or the amount of pasture in the farm is not sufficient, or both, unless extra feed can be supplied during the latter part of lactation.

These facts also indicate that, at the whole system level, a higher level of milk yield at peak lactation is not strictly necessary for achieving the highest annual level of production per cow. While a greater amount of additional feed was required to achieve similar levels of production with autumn-calved cows, the extra cost might well be offset by the potential benefits to the dairy industry from a more even supply of milk over the whole year. In addition, the amounts of extra feed necessary for autumn calving systems seem to be only slightly higher than those required for spring calving systems, with some of their extra feed being derived from extra silage conserved in spring in the autumn calving systems (see Table 4).

Finally, a large number of questions remain to be answered, for example the potential use of changes in calving date to ameliorate the antagonistic effects of peak yields on the reproductive performance of high genetic merit cows, the relationships between calving date and stocking rates for autumn-calving systems, and the better allocation of supplements in those systems. Due to the large number of relationships and interactions between components of the pasture-based dairy system outlined in the present review, it is clear that any attempt to investigate the effects of calving date or calving season on the whole system should be approached by means of systems research, using farmlets, whole farms, and/or simulation models.

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Overview of Chapter 2

Three main conclusions have been drawn from the literature reviewed in the previous chapter. First, that autumn calving systems may perform similarly to the traditional spring calving-based systems provided a minimum amount of supplementary feed is available to the cows. Secondly, that a key factor responsible of this could be the longer lactations that are usually achieved by the autumn-calved cows in pasture-based systems. Thirdly, that because of the large number of interactions acting within the real-world systems, the above 'systems hypotheses' should be tested by means of systems research and/or a modelling approach.

A 3-year calving system study conducted at No 1 Dairy Farm, Massey University tested the first hypothesis, and some preliminary results were mentioned in the literature review. The main physical results of this long-term, systems comparison constitute the central topic of Chapter 2.

Chapter 2

Comparative efficiency of Autumn and Spring calving for pasture-based dairy systems

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Abstract. A three-year experiment involving a large-scale dairy farm was conducted at Massey University, New Zealand, to investigate the comparative efficiencies of contrasting calving systems. The farm was divided into three-40 ha farmlets and three systems in which the cows calved either in autumn (100A), in spring (100S), or half in autumn, half in spring (A-S), were implemented. Stocking rates were 2.0, 2.4, and 2.2 cows/ha, respectively. Autumn-calved cows had greater ($p<0.1$) yields of milk and milksolids due to greater lactation lengths (361 kg MS/cow in 291days vs. 309 kg MS/cow in 241 days for comparisons between 100A and 100S cows, respectively, $p<0.1$) and higher daily yields ($p<0.1$) in mid and late lactation. As a result, the three systems produced very similar ($p>0.1$) amounts of milk and milksolids/ha (723, 750, and 720 kg MS/ha for 100A, 100S, and A-S systems, respectively). Greater ($p<0.1$) amounts of forage were conserved per cow and per ha for 100A (2.43 t DM/ha) than for the other systems (1.0 and 2.0 for 100S and A-S, respectively). However, differences in the quantity fed/ha were much smaller ($p>0.1$). The contribution of grazed pasture to the annual diet of cows was high (80%) and similar ($p>0.1$) for the three systems. In conclusion, contrasting calving systems produced similar amounts of milk/ha, with similar efficiency.

Key Words: Calving Season; Pasture; Dairy Systems

1. Introduction

One of the main features of New Zealand's dairy system is that almost all cows calve during a short period of time in late winter-early spring, in order to synchronise the seasonal changes in pasture growth rate with the seasonal changes of herds' requirements. The consequence of this is a very seasonal pattern of milk supply to the factories, which results in a relatively inefficient utilisation of the installed factory capacity. Calving in autumn rather than in spring may be a valid alternative to alleviate the problem. However, autumn calving in temperate regions is generally perceived as a system in which pasture utilisation is lower and the need for supplementary feeds is greater, so that the general efficiency of the system is lower than for spring-calving systems. While research involving dates of calving in pasture-based dairy systems has focused on the effects of relatively minor changes in calving dates within the spring season (García and Holmes, 1999, Chapter 1), much less emphasis has been placed on the evaluation of different 'calving seasons'. A three-year trial on a large dairy farm was carried out to investigate the effects of changing the calving season either partially (50%) or totally (100%) from spring into autumn, and main results are presented and discussed in this paper. Preliminary results have been published previously elsewhere (García *et al.* 1998).

2. Materials and Methods

The experiment was conducted at Massey University's N° 1 Dairy Farm, Palmerston North, New Zealand, between 1 July 1996 and 30 June 1999. The commercial farm (123.5 ha) was divided into three 40-ha farmlets, with all the soil types (river soils, Rangitikei and Manawatu Series) equally represented among them. Three systems in which the cows calved either all in autumn (100A), all in spring (100S) or in both seasons (A-S), were randomly allocated to each farm. Planned stocking rates were 2.0, 2.5 and 2.25 cows/ha, respectively, although the actual stocking rates achieved were slightly lower for the S (2.4) and A-S (2.2) systems due to unplanned early culling of some cows. The differences in planned stocking rates among the three systems were due to both optimisation results from simulation analyses and the consensus reached by a group of local dairy farmers. Within A-S system, 50% of the cows calved in autumn ("50A") and 50% in spring ("50S"). Calving periods of 10 weeks were planned to start (i.e. 282 days after the day of the 1st mating) on 10 March, 20 July, 20 March, and 1 August for 100A, 100S, 50A and 50S, respectively. The planned delay of 10 days in each calving period for the A-S system was aimed to alleviate the normally higher feed demand early in each season for a system that has lactating cows all year round. All cows were Holstein Friesians of similar Breeding Worth at the beginning of the trial (herd average ± SD = 26 ± 0.8).

Pasture measurements included whole farm herbage mass (HM) weekly, pre- and post-grazing HM daily, and pasture quality monthly. Herbage mass was estimated on each paddock with a Rising Plate Meter (RPM), which was calibrated by cutting 54 × 0.2 m^2 quadrats to ground level on 3 occasions during the spring of Year 1 only. The pooled calibrated equation was similar to the general relationship commonly used by NZ farmers in previous years [HM (kg DM/ha) = 200 + 158*ch*), where *ch* ('compressed-height') are the RPM readings based on 0.5-cm units. Therefore, that equation was adopted for all 3 years. Pasture growth rate (PGR) was estimated either by the change in HM of all the paddocks not grazed during a week (method 1, used during the 3 years) or by the difference (for every paddock) between the HM left as residual yield after one grazing and the HM available before the next grazing (method 2, used from January 1997 to June 1999). Pastures were mainly based on perennial rye grass (*Lolium perenne L.*) and white clover (*Trifollium repens L.*), although cocksfoot (*Dactylis glomerata L.*), prairie grass

(*Bromus willdenowii K.*) and tall fescue (*Festuca arundinacea L.*) were also present in some paddocks.

The same decision rules for grazing management were applied to all farms during the three years. They included the maintenance of the average whole-farm HM at around 2000 kg DM/ha, post-grazing residual HM for lactating cows no less than 1600 kg DM/ha and pre-grazing HM about 2600 kg DM/ha. Grazing decisions were made weekly using the above guidelines and the results of a simple balance between the herds' requirements and the pasture growth rate for the next week. Forage harvested from each farm (conserved as either silage or haylage) and maize silage (harvested on farm in Year 1 and purchased in Years 2 and 3) were the only supplements fed to the cows whenever a potential deficit in pasture intake was apparent. Maize silage was included in the diet of autumn-calved cows in early lactation, regardless of the amount of grass silage available for those systems. This was done with the aim of providing some energy from a grain-source in the period of maximum requirements (both productive and reproductive) and minimum pasture availability (winter).

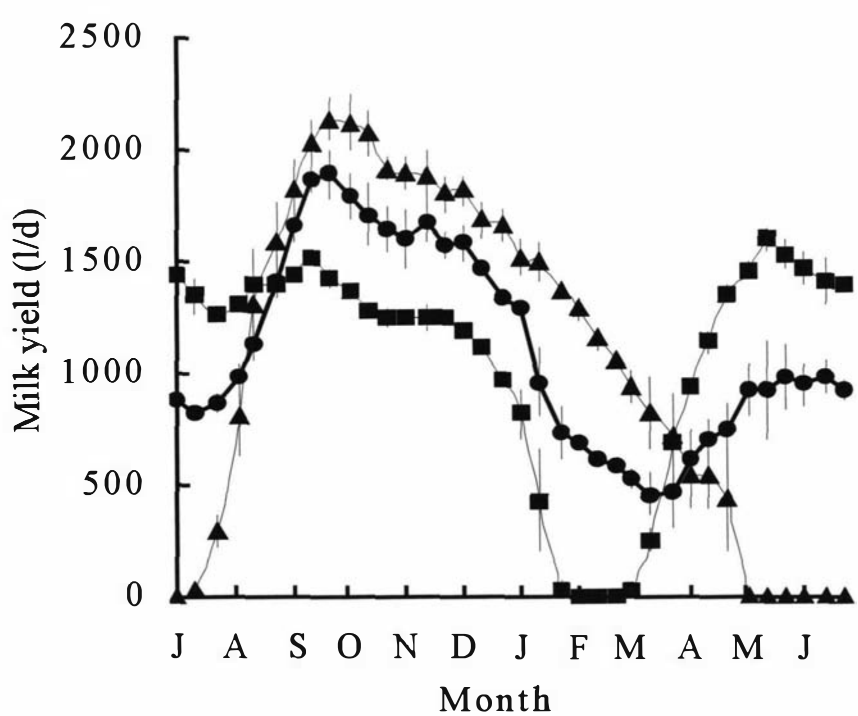
Milk yield for each herd was recorded daily by using load cells on the milk vat. Once per week the milk from each herd was collected separately and a sample was taken for analysis of milk composition. Milk production and composition of individual cows were measured by herd tests, monthly during the first twelve months of the trial, and fortnightly during the second and third years. All supplements harvested, purchased and fed to the cows were weighed (wet basis) and samples taken to calculate % of DM. Samples were also taken periodically while the supplements were being fed, to calculate % of DM, total DM fed, and for chemical analysis. Two days before herd-testing, pastures from two different paddocks for each system (the paddocks which were scheduled to be grazed around herd-testing date), were sampled following the procedure proposed by Cosgrove *et al.* (1998). Pasture samples were pooled by paddock, oven-dried at 60° C for 48 h, and N content, in vitro DM digestibility, NDF, ADF, and ash, were estimated by NIRS (Corson *et al.* 1999). Apparent pasture dry matter intake (DMI) was estimated daily for each herd from the difference between the pre- and post-grazing HM (method 2). Live weight and body condition score were recorded monthly for each cow. All health related treatments and/or reproductive events were recorded for every cow.

Because replication was not feasible, a direct t-test for comparing treatments is not possible (Maindonald, 1992). To overcome this limitation, data for farmlets were analysed as a Complete Randomised Design, with years as replicates, or using individual animals and paddocks as experimental units for some milk- or pasture-related variables, respectively. Lactation curves of individual cows were analysed as a split-plot design with time (month of lactation) as repeated measure. In addition, a non-linear model was fitted to the lactation data prior to analysis and results of the comparison between methods are published elsewhere (García *et al.* 2000, Chapter 3). Month of lactation (0-1, 1-2, etc.) was used as the repeated variable. Because of the nature of the experiment, significance was declared at $p<0.10$ unless otherwise stated.

3. Results and Discussion

Contrasting calving systems resulted in very different annual patterns of milk supply to the factory (Figure 1). However, despite these differences in stocking rate and in the supply pattern between the farms, the three systems produced very similar ($p=0.32$) total quantities of milk and milksolids (MS=milk fat + milk protein) per ha, due to significantly ($p=0.07$) greater yields of MS/cow by 100A than for 100S (Table 1). Autumn-calved cows had longer ($p<0.05$) lactations than spring-calved cows (Table 1), compared either between farms (100A vs 100S) or between herds within a farm (50A vs 50S).

Fig. 1. Ten-day averages of daily milk supply for 100A (■), 100S (▲) and A-S (●) systems. Values are means across the 3 years. Vertical bars represent SD/√n, where n (number of years) =3.



Thus, autumn calving systems compensated for their lower stocking rates by higher yields of milk and MS per cow, resulting in similar yields of MS produced per ha for the three systems. These higher yields per cow were the combined result of both longer lactation lengths (Table 1) and greater yields of milk and MS during mid and late lactation (Figure 2). The fact that these results were observed not only between farms (100A vs 100S) but also between herds within the A-S farm (in which both herds were grazed together and stocked at the same rate), suggests that those effects were truly due to differences in calving seasons, and not to differences in stocking rates. These findings are in general agreement with other results (García and Holmes, 1999, Chapter 1). In Victoria, Thomas *et al.* (1985) reported a 17% higher milk fat yield by autumn-calved cows than for spring-calved cows, both stocked at 2 cows/ha. Ryan (1999) observed a 6% increase in milk yield per cow in a similar 2-year comparison in Ireland, in which both systems were stocked at 2.5 cows/ha. However, in a systems comparison in Tasmania, Fulkerson *et al.* (1987) reported lower milk fat yields (4.3%) for autumn-calved cows than for spring-calved cows, despite the lower stocking rate of the former (1.45 vs 1.6 cows/ha). This latter study was, however, the only one in which only supplements of forage conserved on the farm were used, a fact that probably resulted in an underfeeding of autumn-calved cows during winter, as suggested by García and Holmes, (1999) (Chapter 1). The concentrations of milkfat, milk protein and MS did not differ (p>0.1) between farms (Table 1).

Table 1. Effect of calving season on milk production, milk composition and lactation length of whole-farm dairy systems[1].

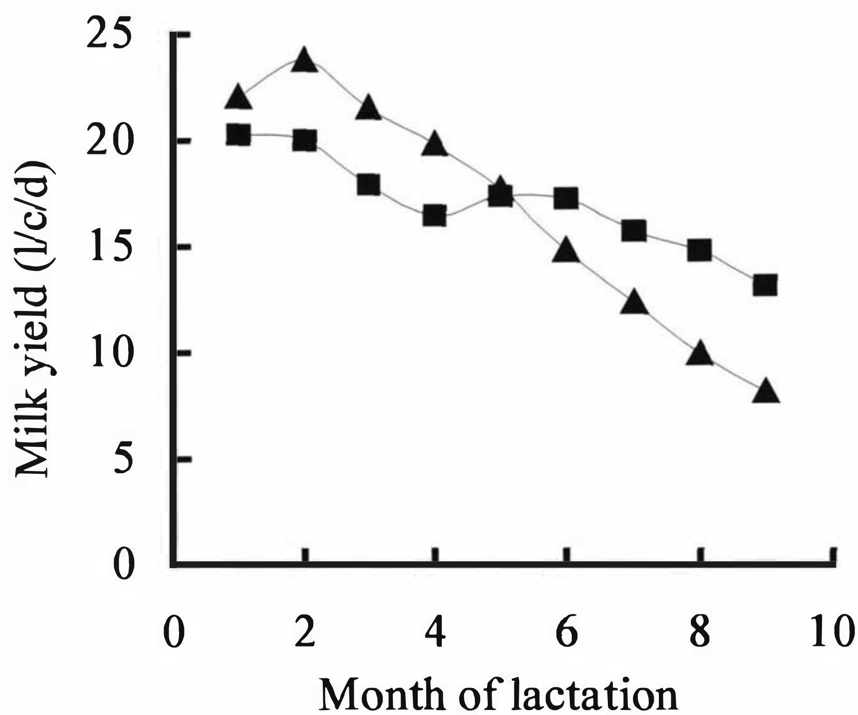
Item	Farms (Calving systems)				SE
	100A	100S	A-S 50A	A-S 50S	
Milk yield (l/ha)[2]	9004	9442	9035		161.9
Milksolids (kg/ha)[2]	723	750	720		13.9
Milksolids (kg/cow)[2]	361[a]	309[b]	333[ab]		12.9
Milkfat (%)	4.61	4.53	4.52		0.03
Milk protein (%)	3.46	3.46	3.46		0.02
Milksolids (%)	8.07	7.99	7.98		0.05
Lactation length (d)	291[a]	241[b]	279[a]	237[b]	12.4

[1] Means and SE were calculated using years as replicates
[2] Calf-milk not included; milksolids= fat + protein
[a,b] Values on the same line with different superscripts are significantly different (p<0.1)

The analysis of individual lactations showed a strong interaction between season of calving (farms) and stage of lactation, and these results are presented in more detail in Chapter 3. Consistently over the 3 years, autumn-calved cows had lower ($p<0.05$) daily milk yields at peak of lactation, but higher ($p<0.05$) yields of milk and MS during mid and late lactation (Figure 2). These observations concur with those of previous research studies (Auldist *et al.* 1997; Ryan, 1999) as well as with results from a survey of commercial farms in New Zealand (Chang'endo, 1996).

Means of milk yield for each month of lactation did not correlate significantly with pasture quality variables (see Chapter 3). Annual net herbage production, estimated by either method 1 or method 2 (see Chapter 5), was similar ($p>0.1$) for all three systems (Table 2). Average HM on offer for the 3 years were close to target (2000 kg DM/ha) on the three farms.

Fig. 2. Average milk yields by month of lactation for 100A (■) and 100S (▲) systems. Values are means across the 3 years.



Greater ($p<0.05$) quantities of forage DM were conserved as supplements (both per cow and per ha) for the 100A than for 100S (+145%/ha) or the A-S (+22%/ha). Cows in the 100A farm were fed 77% more ($p<0.1$) conserved forage (DM basis) than cows in 100S. However, while both systems needed to purchase about 50% of their total supplementary needs (maize silage for 100A but mainly grass silage for 100S), the 100A system had a surplus of grass silage equivalent to the total amount of maize silage purchased, suggesting that either similar results might have been achieved without purchasing any extra feed, or that the stocking rate could have been higher. The latter is probably a more attractive option as previous evidence suggests that early lactation cows perform better with a mixture of maize and grass silage rather than with grass silage as the only source of forage DM (O'Mara *et al.* 1998). The larger amounts of supplementary feed conserved and used per cow for 100A than for 100S systems are also in agreement with results of previous studies (Thomas *et al.* 1985; Ryan, 1999). However, due to the lower stocking rate of the 100A system, the differences in the amount fed per ha were not significant (p>0.1, table 2). Further, a variable proportion of the spring-calved cows was grazed-off farm during the three winters of the experiment. Considering this grazing-off as a "supplement" (assuming an average intake of 8 kg DM/cow daily), the differences in the amount of supplements fed per ha almost disappeared completely (Table 2). Moreover, the amount harvested and fed out per ha were in balance for 100A system, but the 100S had a deficit of supplements of 0.67 t DM/ha (average of 3 years).

Table 2. Effect of calving season on total pasture grown, harvested and on the amounts of total supplementary feed consumed by the cows[1].

	Farms (Calving Systems)			
Item	100A	100S	A-S	SE
Pasture grown (t DM/ha.year)[2]				
Method 1	11.6	12.2	11.5	0.97
Method 2	11.9	11.3	12.1	0.31
Conserved forage (t DM)[3]				
harvested per ha	2.43 ^{a}	0.99 ^{b}	1.98 ^{a}	0.34
fed per ha	2.34	1.66	1.69	0.25
fed per ha (including grazing-off)[4]	2.40	2.20	2.30	0.20
Total DM intake (kg/cow/day)	15.1	13.5	15.5	0.53
Diet composition (%)[5]				
Grazed Pasture	78.6	80.2	79.7	3.45
Maize silage	10.0 ^{a}	0 ^{c}	6.5 ^{b}	0.64
Pasture silage	10.0 ^{b}	14.8 ^{a}	10.9 ^{b}	1.10
Haylage	1.0	5.2	2.7	2.13

[1] Means and SE were calculated using years as replicates

[2] Both methods estimate net herbage production. Method 2 includes data for Years 2 and 3 only.

[3] Supplements harvested are basically pasture silage, but include some haylage made during Year 1. Supplements fed include pasture silage, haylage and brought-in maize silage.

[4] Grazing-off farm calculated as Number of cows x days x 8 kg DM/cow.

[5] Pasture intakes based on method 2 (Years 2 and 3 only). All supplemetary feed offered to the cows was weighed on a daily basis.

[a,b,c] Values on the same line with different superscripts are significantly different (p<0.1)

Autumn-calved cows consumed more supplement DM than spring calved cows, but also had longer lactations and greater total milk yields (and therefore higher feed requirements). Thus, total daily DM intake tended ($p=0.12$) to be higher for 100A cows than for the 100S cows and consequently, the relative contribution of grazed-pasture to the cows' diet was very similar ($p>0.1$) among farms (at least 75% of total DM eaten).

On average, autumn-calved cows were 5.5% heavier ($p<0.1$) than spring-calved cows, although average body condition scores were similar ($p>0.1$) for all herds (Table 3). Neither the interval between calving date and date of first insemination, nor the submission rate 4 weeks after the start of the mating period, or the final rate of non-pregnant cows, were significantly affected ($p>0.1$) by season of calving. This is in contrast with results from a survey of dairy farms in New Zealand, in which autumn calving systems appeared to have lower reproductive performance (Chang'endo, 1996), and contrast with other results from Tasmania (Fulkerson *et al.* 1987).

Table 3. Effect of calving season on the average liveweight, body condition score, and reproductive performance of cows[1].

Item	Farms (Calving Systems)				SE
	100A	100S	A-S		
			50A	50S	
Liveweight (kg/cow)	508[a]	487[b]	508[a]	476[b]	7.4
Body condition score (1-10)	4.69	4.62	4.52	4.51	0.09
Calving to 1st service (d)	74.6	70.6	73.6	73.6	3.4
4-wk SR (%)[2,3]	91	91	87	89	5.0
Empty rate (%)	13.7	15.7	16.7	14.0	4.1

[1] Means and SE were calculated using years as replicates
[2] Submission rate after 4 weeks of artificial breeding
[3] Percentages are related to total number of cows mated
[a,b] Values on the same line with different superscripts are significantly different ($p<0.1$)

4. Conclusion

Similar yields of MS per ha were obtained with three very contrasting systems of milk production. The common farmers' 'perceptions' with regards to the lower efficiency of autumn calving systems compared to the traditional, spring calving system, are not supported by the results of this study.

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Overview of Chapter 3

Chapter 2 presented the main physical results of the 3-year systems study. Overall, contrasting calving systems performed very similarly in terms of physical production, despite differences in stocking rate between the systems. Some of the key factors responsible for this overall similar performance, such as the differences in the shape of the lactation curves and total yields by autumn- and spring- calved cows, have been briefly identified in the literature review (Chapter 1), and also in Chapter 2. A more complete study of these lactation curves during the 3 years is the topic of the next chapter, Chapter 3.

Chapter 3

Lactation curves of autumn- and spring-calved cows in pasture-based dairy systems

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Abstract. A linear-based and a non-linear-based method for the analysis of lactation curves were evaluated in this study to investigate the effects of calving season on the shape and length of the lactation curve, total milk yield, milk composition and somatic cell counts of autumn- and spring-calved cows. Lactation records from a three-year systems study in which cows calved either in the autumn or in the spring, were analysed by either split-plot analysis of test-day data, or by fitting the diphasic equation of Grossman and Koops (1988) prior to analysis by linear models. Average lactation curves produced by both methods were similar. Lactation curves of spring-calved cows were "normal", with a peak followed by a steady decline. However, lactation curves of autumn-calved cows were different in shape, with lower yields at peak of lactation but higher yields in mid and late lactation, which resulted in a significant interaction ($P < 0.01$) between calving season and stage of lactation. The greater yields in mid and late lactation by the autumn-calved cows, together with their longer lactations (despite the fact that the same guidelines were applied for deciding the drying-off of all cows), resulted in greater total milk yields for these cows. Somatic cell counts were greater ($P < 0.05$) in mid and late lactation for the spring-calved cows than for the autumn-calved cows, due probably to a dilution effect. A conceptual model is presented, in which the observed differences in the shapes of the lactation curves of autumn- and spring-calved cows are referred to the cows' potential yield.

Keywords: Grazing dairy cows; Lactation curve; Calving season; Pasture-based systems; Model fitting

1. Introduction

Typical lactation curves of dairy cows show a peak or maximum daily yield occurring between 4 to 8 weeks after calving, followed by a daily decrease in milk yield (rate of persistence) until the cow is dried-off, or the lactation is naturally terminated (Keown *et al.* 1986). Lactation curves of dairy cattle grazing in temperate regions, however, can differ significantly in shape from that typical curve, mainly because of the seasonality of pasture production (Wood, 1972). In New Zealand and in other temperate countries, where the physiological demand of the cows is synchronised with the pasture supply, almost all cows are in early lactation during the period of maximum availability of quality pasture (spring). This suggests that 'seasonal' and 'physiological' effects on the shape of the lactation curve are confounded for cows that calve in spring, but not for cows that calve in autumn.

An important characteristic of these early-spring calving systems is that the cows are normally dried off in late summer-early autumn, usually because either their body condition or the pasture availability in the farm is less than optimum, or both (Holmes *et al.* 1987), which results in very short lactation lengths of about 220-240 days (Livestock Improvement Corporation, 1997).

Changing the calving season from spring to autumn in temperate regions has been proposed as an alternative to increase the supply of milk during autumn and winter and to reduce the large peak of milk supplied to the industry in spring (García and Holmes, 1999). This would enable the dairy industries of countries with temperate climates in general, and that of New Zealand in particular, to benefit from the more complete utilisation of the installed factory capacity. However, the impacts of changes in the calving season on the whole system and on the shape of the lactation curves must be assessed. Further, because lactation lengths of New Zealand dairy cows depend markedly on the cows' body condition and feed availability, the effects of calving season on the length of lactation is of particular interest.

Lactation curves of dairy cows can be studied by fitting either empirical (linear or non-linear), mechanistic (Beever *et al.* (1991), or non-parametric models to the data (Elston *et al.* 1989). Despite the potential advantages of the more complex mechanistic models (see review by Beever *et al.* (1991)), the simpler empirical models continue to be the preferred option by many researchers (e.g. Pérochon *et al.* 1996; Olori *et al.* 1999; Tozer and Huffaker, 1999). However, an even simpler approach to study the lactation curve of a group of cows is the categorical analysis of test-day data by linear models, in which data are classified into time intervals. Although this approach has been compared previously with non-linear models fitted to individual lactation curves (Scott *et al.* 1996), the advantages and limitations of linear-based (categorical analysis), and non-linear-based methods for studying lactation curves of grazing cows in pasture-based systems have not been addressed.

In this study, a linear-based method (categorical analysis) and a non-linear-based method for the analysis of lactation curves were evaluated with the objective of studying the effects of calving season (autumn or spring) and calving system (100% autumn, 100% spring, or 50%/50%) on the shape and length of the lactation curve, total milk yield, milk composition, and somatic cell counts of autumn- and spring-calved cows.

2. Materials and Methods

2.1. System experiment and lactation records

A whole-farm systems comparison was carried out at Massey University N° 1 Dairy Unit from 1 July 1996 to 30 June 1999, to study the effects of calving season on the productivity and profitability of the dairy farm enterprise. The 120-ha property was split into three 40-ha farms, by randomly allocating the 61 available paddocks. Thus, each farm was similar with respect to total area, number of paddocks, and distribution of soil types. Three systems in which Holstein-Friesian cows calved either all in autumn (100A), all in spring (100S), or half in autumn and half in spring (50/50, or 50A and 50S when referring to the individual subherds, respectively), were randomly assigned to the farms. Stocking rates averaged across the 3 years were 2.0, 2.4, and 2.2 cows/ha, respectively, and each farm system was managed independently and to its own advantage, using a common set of management guidelines for decisions about grazing, use of supplementary feed, and duration of the lactating period (García *et al.* 2000). Cows in the three systems were of similar parity number and distribution (average = 3.7; with 24%, 18%, 16%, and 42% of cows in 1st, 2nd, 3rd, and 4th or more parities, respectively), and were weighed and condition-scored monthly. Cows in all systems were dried-off either when their body condition score was less than 3.5 (scale 1-10), or when pasture availability (average herbage mass) in their respective farms was less than 2000 kg DM/ha, or both, as is the common practice in New Zealand dairying.

Daily milk yields of all lactating animals in the trial were measured by herd-test from consecutive morning and afternoon milkings (Livestock Improvement Corporation, Ltd), monthly during Year 1, and fortnightly during Years 2 and 3, resulting in a total database of approximately 11000 herd test records from 450 cows and 937 individual lactations. On each testing date, an aliquot of milk from each cow was collected and later analysed for milk fat, milk protein, and somatic cell count (SCC) using a Milkoscan (AnFoss, Denmark).

Pastures samples were taken by hand-plucking a few days prior to each herd-test (Cosgrove *et al.* 1998). On each sampling date, and for each calving system, samples were taken from the two paddocks which were scheduled to be grazed immediately before each herd test. Restricted quantities of supplements (maize silage and grass silage) were fed to cows whenever a deficit in pasture availability was anticipated (García *et al.* 2000). Samples from pastures and supplements were analysed by near infra-red spectroscopy (Corson *et al.* 1999) for contents of dry matter (DM), organic matter (OM), crude protein (CP), neutral detergent fibre (NDF), acid detergent fibre (ADF), soluble carbohydrates (SC), *in vitro* OM digestibility (IVOMD), and metabolisable energy (ME). All the data for pastures, intakes, body condition score, and liveweight are being published separately, and other details of the design of this experiment are given by García *et al.* (1998) and García *et al.* (2000).

2.2. Methods

Milk yield data were utilised to evaluate two different methods for the analysis of lactation curves. In method 1 ("Test-day" model), discrete intervals, based on the calving date of each cow, were created to classify herd-testing sampling dates. Intervals of 10, 30, and 90 days were first evaluated, although the monthly intervals were finally adopted, because they provided the best balance between number of recording-dates included in a single time interval, and the variation within that interval. In addition, 10-day intervals were too short for the monthly-interval data of Year 1. Thus, for this method, each single herd test record added information to the mean values of the corresponding month of lactation (MOL); MOL 1 represents the period between 0 to 30 days of lactation, MOL 2 represents the period between 30 to 60 days, etc.

Data were analysed as a mixed-model (Littell *et al.* 1998), assuming a Compound Symmetry covariance structure in the Proc Mixed of SAS (1990). The model utilised was:

$$Y_{ijkl} = \mu + CS_i + MOL_k + (CS_i \times MOL_k) + Cow_j(CS_i) + \varepsilon_{ijkl}$$

Where Y_{ijkl} = daily milk yield, defined by the population mean μ, plus the fixed effects of the i Calving System (CS), the k MOL, and the interaction of the i CS × the k MOL, the random effects of the j cow within the i CS and the experimental error ε_{ijkl}. Adjusted lactation curves were constructed using the least square means of the interaction CS × MOL.

In method 2 ("Non-linear" model), the multiphasic equation proposed by Grossman and Koops (1988) was fitted to the data prior to the analysis of its parameters by conventional general linear models. The multiphasic equation has been successful applied in previous studies (e.g. Weigel *et al.* 1992) and was selected in the present study as visual inspection of the lactation curves for the autumn-calved cows showed two "peaks of lactation". Therefore, the more simple published models, such as the incomplete gamma function of Wood (1967), were discarded due to their inability to model more than one lactation peak. The equation used was:

$$Y_t = \sum_{i=1}^{2} \{a_i b_i [1 - \tanh^2(b_i(t - c_i))]\} \qquad (1)$$

Where Y_t= is milk yield at time t (days since calving); a = half the asymptotic yield (l/cow), b = rate of yield relative to a (l^{-1}); c = time to achieve the peak (days). Other statistics derived from equation (1) are the peak yields of each phase (computed as $a_i b_i$), and the duration of each phase, which is defined as days required to achieve 75 % of asymptotic yield (computed as $2b_i^{-1}$).

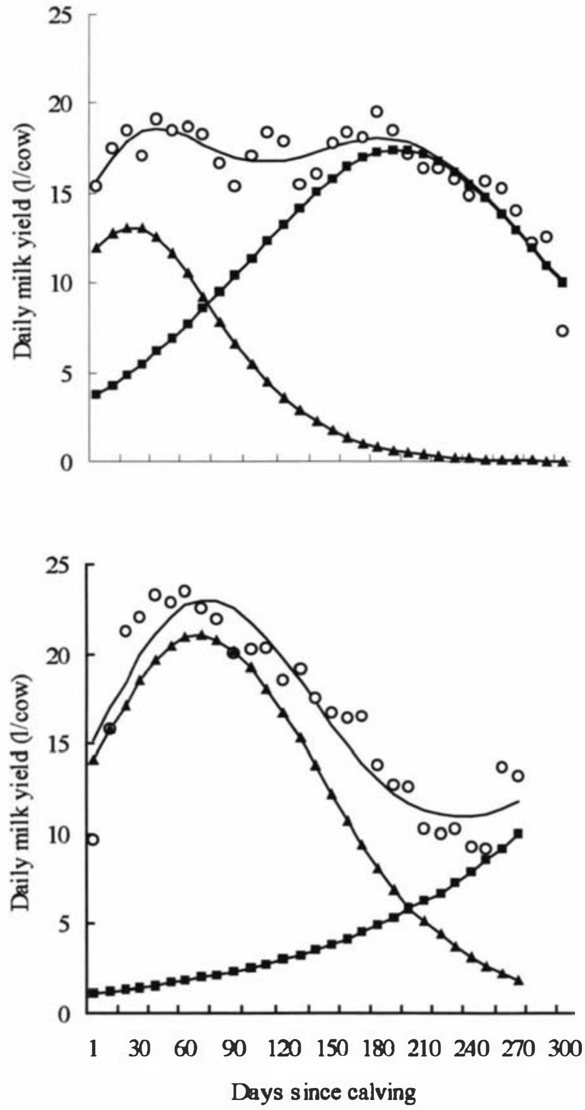
Cumulative milk yield ($Y_{(cumulative)}$) at time t is estimated as the integral of equation (1) with respect to time t, from -∞ to ∞:

$$Y_{(cumulative)t} = \sum_{i=1}^{2} \{a_i [1 + \tanh(b_i(t - c_i))]\} \qquad (2)$$

Equation (1) was first fitted to the average lactation curve of both the 100A and the 100S herds (Fig. 1), to ensure that the same equation could be used to successfully model contrasting shapes of lactation curves. Equation (1) was fitted to the data of each individual cow thereafter. In both cases, the equation was fitted using the Gauss-Newton method available in the Proc NLIN of SAS (1990). When fitting individual animals, the parameter values obtained for the herds lactation curves were used as initial values for the iterative process.

Cows with abnormal or incomplete lactations were omitted because either the total number of test-day records per lactation was less than 7 (167 lactations), or the resulting fitted curves were very abnormal (370 lactations). Thus selection criteria included records with: ≥ 7 herd tests per season; a_i < 5000 litres; 10 < $peak_{(phase\ 1)}$ (litres/cow/day) <35; and $peak_{(phase\ 2)}$ ≤ 30 litres/cow/day, resulting in a final data set (for method 2 only) of 400 individual lactations.

Fig. 1. Ten-day averages of actual (○) daily milk yields by autumn-calved cows (top) and spring-calved cows (bottom). Values were fitted with the diphasic lactation curve (—), which results from the summation of a first phase (▲), and a second phase (■).



Parameters and statistics derived from equation (1) were analysed for each year of the trial (Proc GLM of SAS (1990)) using the linear model:

$$Y_i = \mu + CS_i + \varepsilon_{ij}$$

Where Y_i = is a function of estimates for the parameters and statistics of interest, μ is the general mean, CS_i is the effect of the i calving system, and ε_i is the residual effect.

2.3. Comparison of the two methods

In order to compare the curves produced by each method, LSMEANS for each MOL in method 2 were calculated using equation (1) for t = 15, 45, 75, ...285, which represented the average dates for MOL = 1, 2, 3,... 10, respectively.

The mean square prediction error (MSPE), and the mean prediction error (MPE, defined as the square root of MSPE expressed as percentage of the averaged yield), were used as a measure of the difference between the two methods (Bibby and Toutenburg, 1977). The MSPE was calculated as $\sum(A-P)2 / n$, where A are the "actual" means (method 1), P are the "predicted" means (method 2) and n is the number of pairs of A and P values being compared. MSPE can be expressed as the sum of three independent terms: mean bias or general tendency, bias around the regression line, and random disturbance. Relatively greater MSPE due to bias around the regression line is indicative of the intrinsic inadequacy of a model to predict a particular set of data (Bibby and Toutenburg, 1977). Overall predictions were considered to be satisfactory, adequate, or unsatisfactory, when MPE was < 10 %, between 10 and 20 %, or > 20 % (Fuentes-Pila *et al.* 1996). Least square means obtained by method 1 were assumed to be the actual values for this purpose.

3. Results

3.1. Quality of pasture and supplements

Seasonal average values for the chemical composition of pastures and supplementary feeds are shown in Table 1. Overall, pastures were of lower nutritive value during summer, with higher ($P < 0.05$) contents of ADF and NDF, and lower ($P < 0.05$) contents of CP, SC, and ME, than during the rest of year. These differences were accentuated in Years 2 and 3, due to the soil moisture deficits and slower herbage accumulation rates that occurred during the summers of those years (unpublished data).

Supplements were of relatively good quality in terms of the concentrations of ME (range = 10.4-11.3 MJ/kg DM), CP (range = 15.2-19.6 g/100 g DM for grass silage), and NDF (range = 40.9-55.5 g/100 g DM). Maize silage was fed almost exclusively to autumn-calved cows in early lactation (April-July). Grass silage was fed in early lactation for autumn-calving cows, but in mid and late lactation for the spring-calved cows (January-April). All cows were fed solely on grazed pasture during the spring.

Table 1. Chemical composition of pasture (by season) and supplements for the three years.

Year	Feed[2]	Season[3]	Chemical composition[1]						
			DM	CP	ADF	NDF	SC	Dig	ME
			%	% of DM					MJ/KgDM
		Winter	...	...	...	...	...	...	...
		Spring	22.8^{a}	20.6^{b}	25.0^{b}	47.0^{ab}	10.6^{a}	74.8^{a}	11.8^{a}
	Pasture	Summer	21.8^{a}	17.7^{b}	29.6^{a}	50.0^{a}	7.97^{b}	70.7^{b}	11.1^{b}
1		Autumn	15.4^{b}	25.4^{a}	25.3^{b}	43.9^{b}	6.64^{c}	74.6^{a}	11.8^{a}
		SE[4]	1.40	1.29	0.98	1.50	0.43	0.87	0.14
	MS	-	29.0	7.3	26.4	53.1	37.8	ND[5]	10.5
	GS	-	25.0	15.2	40.1	55.5	2.3	64.7	10.4
		Winter	18.6	23.5^{a}	22.2^{c}	38.9^{c}	11.4^{a}	77.4^{a}	12.2^{a}
		Spring	18.1	22.9^{a}	25.8^{b}	43.1^{b}	8.43^{b}	74.2^{a}	11.7^{a}
	Pasture	Summer	21.9	18.0^{b}	29.7^{a}	48.5^{a}	7.67^{b}	66.6^{b}	10.1^{b}
2		Autumn	19.9	24.8^{a}	23.3^{c}	42.2^{b}	8.68^{b}	68.6^{b}	10.2^{b}
		SE	1.92	1.25	0.88	1.15	0.63	1.73	0.27
	MS	-	30.0	7.7	24.0	40.9	ND	ND	10.8
	GS	-	27.3	19.5	35.7	51.4	3.0	66.5	10.6
		Winter	16.6^{b}	26.2^{a}	20.6^{b}	38.1^{c}	8.64^{ab}	75.1^{ab}	11.2^{ab}
		Spring	17.9^{b}	24.8^{a}	22.4^{b}	43.4^{b}	9.62^{a}	78.2^{a}	11.7^{a}
	Pasture	Summer	32.1^{a}	15.3^{b}	30.0^{a}	52.5^{a}	7.34^{b}	60.6^{c}	9.0^{c}
3		Autumn	21.2^{b}	26.5^{a}	20.6^{b}	41.0^{bc}	9.55^{a}	74.1^{b}	11.0^{b}
		SE	1.81	1.17	0.86	1.30	0.79	1.96	0.30
	MS	-	31.5	7.5	27.4	44.6	ND	ND	10.4
	GS	-	25.1	19.6	33.2	48.5	2.4	70.6	11.3

[1] DM= dry matter; CP= crude protein; ADF= acid detergent fibre; NDF= neutral detergent fibre; SC= soluble carbohydrate; Dig= digestibility; ME= Metabolizable energy.
[2] MS = Maize Silage; GS = Grass Silage.
[3] Within a year but between seasons, pasture values with common superscripts did not differ ($P < 0.05$).
[4] Maximum Standard Error of LSMEANS.
[5] ND = not determined.

3.2. Linear- and non-linear-based methods for analysis of lactation curves

Fitting the diphasic equation to the data of individual cows (method 2) resulted in about 58 % (range 55 % to 63 %) of the total records being deleted prior to analyses by general linear models. Lack of convergence (including fewer than 7 herd tests per cow) and 'outlier' peaks of lactation were the criteria that accounted for the greatest proportion (average of the 3 years = 46 %) of the total deleted records.

However, despite the loss of more than half of the available records with the non-linear approach, the lactation curves of autumn- and spring-calved cows obtained by this method were similar to their respective curves obtained by method 1 (which are assumed to be 'actual' curves). This was true for the autumn- and spring-calved cows both in comparisons between calving systems (100A and 100S, Fig. 2), and in comparisons within a calving system (50A and 50S, data not shown), although the MSPE and the MPE were higher for the latter case (Table 2).

Fig. 2. Lactation curves for Years 1 (left), 2 (middle), and 3 (right) for 100A cows (top), and for 100S cows (bottom), created with the monthly least square means of milk yield data obtained by applying method 1(▲) or 2 (■). Vertical bars represent standard errors of the least square means.

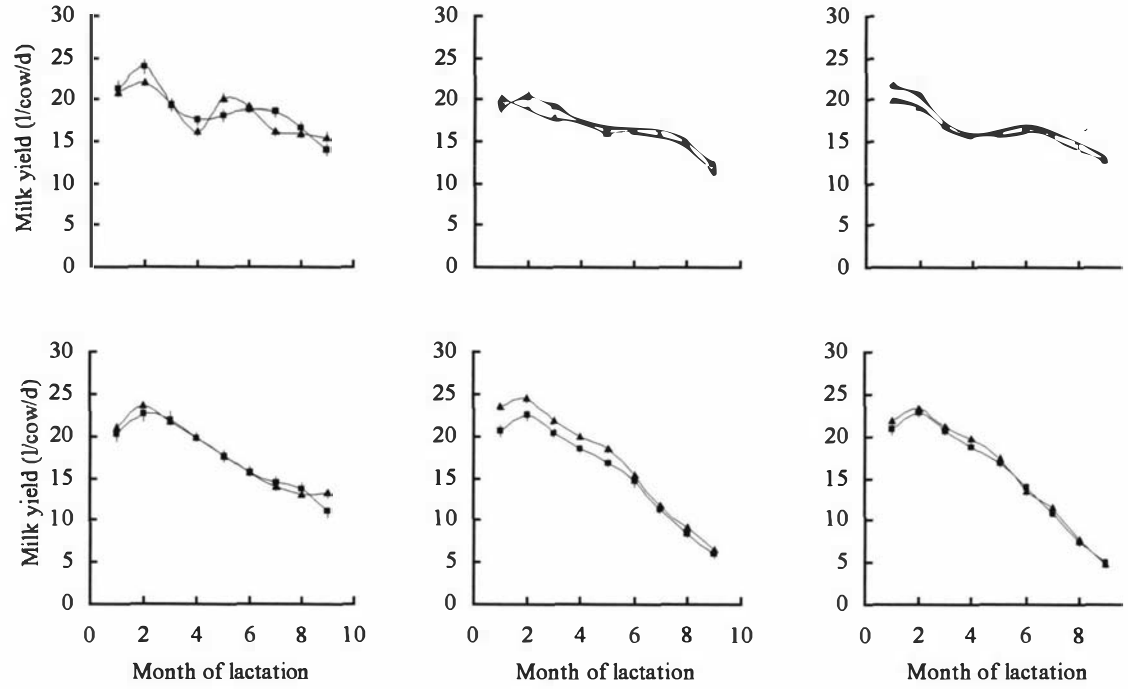
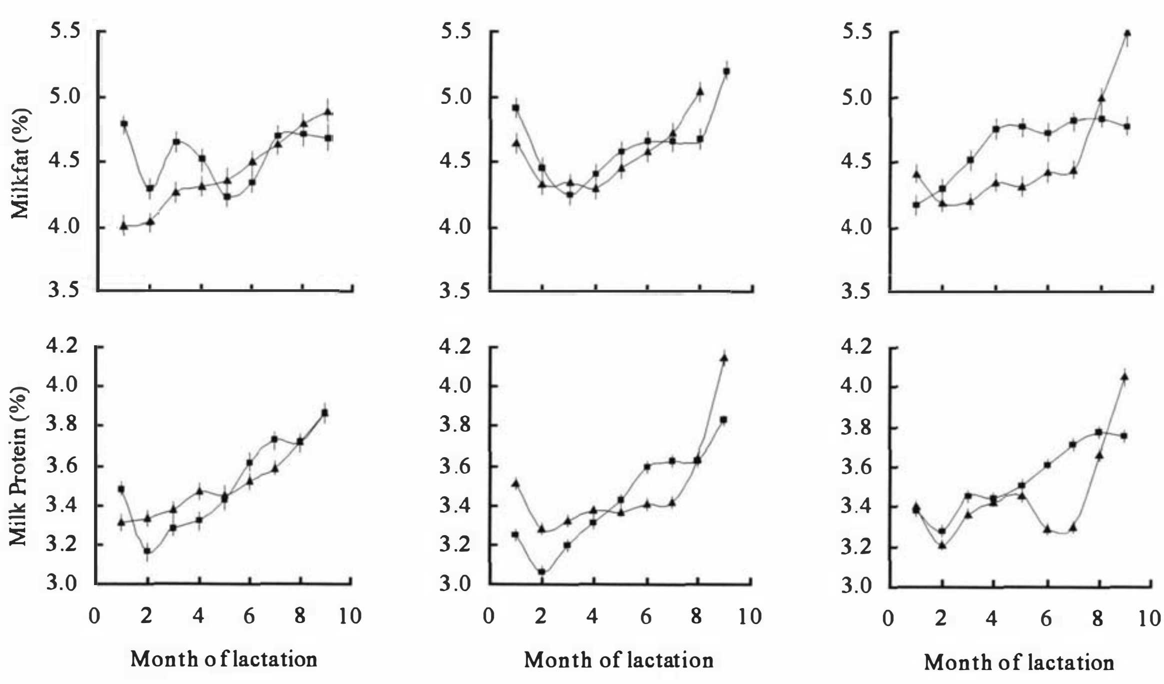


Fig. 3. Curves of daily milk fat (top), and protein (bottom) concentrations (least square means, method 1) for 100A (■) and 100S (▲) cows for Years 1 (left), 2 (middle), and 3 (right). Vertical bars represent standard errors of the least square means.



The largest differences (measured as MPE) between the two methods were observed for the 50A herd, in Years 1 (MPE = 10.4 %) and 2 (MPE = 10.9 %). In all other herds and for all years, the difference between the methods was always lower than 10 % (Table 2). Overall, the bias around the regression line accounted for the smallest proportion of the total mean errors of prediction. Residuals (values obtained by method 2 – values obtained by method 1) plotted against MOL appeared to be randomly distributed across stages of lactation (data not shown), although the non-linear-based method (method 2) slightly overpredicted daily milk yields for autumn-calved cows and slightly underpredicted yields for the spring-calved cows (Fig. 2).

Table 2. Mean square prediction error (MSPE), mean prediction error (MPE), and percentages of total MSPE attributed to bias around the regression line between LSMEANS calculated by method 1 and 2.

	MSPE[a] (litre^2)	MPE (%)	Bias around the regression line (%)[b]
Year 1 (1996-1997)			
100% Autumn	2.0	7.7	21.1
100% Spring	0.8	4.9	2.9
50% Autumn	3.5	10.4	22.6
50% Spring	1.9	7.3	13.2
Year 2 (1997-1998)			
100% Autumn	0.8	5.6	0
100% Spring	2.3	8.9	16.0
50% Autumn	3.7	10.9	12.1
50% Spring	1.6	7.6	11.6
Year 3 (1998-1999)			
100% Autumn	0.7	5.2	26.4
100% Spring	0.3	3.8	14.0
50% Autumn	2.0	8.9	1.3
50% Spring	2.9	9.8	4.4

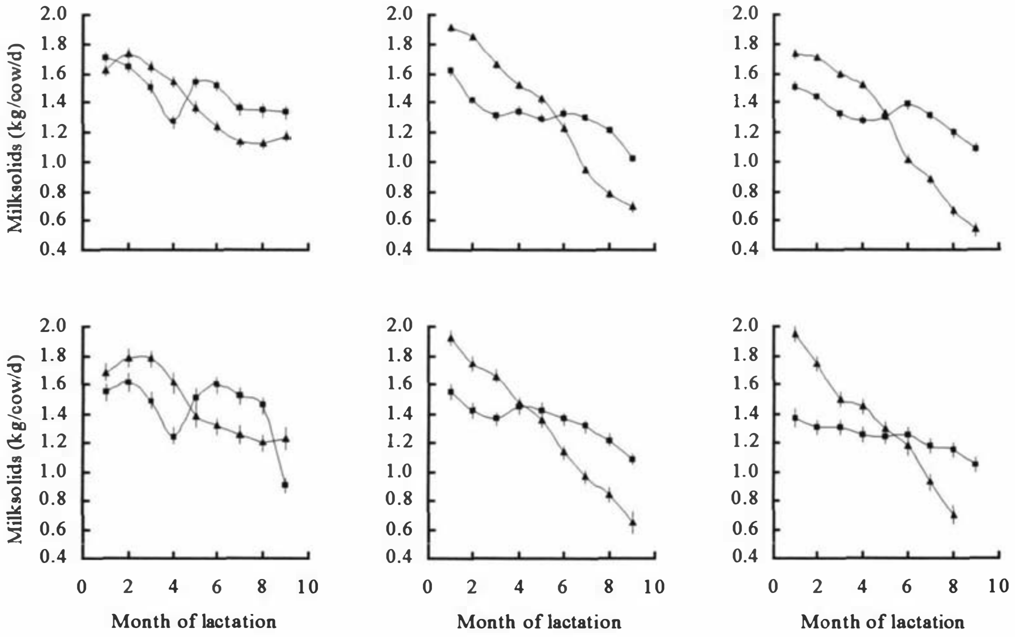
[a] MSPE was calculated as $\Sigma(A-P)2 / n$, where A and P are the LSMEANS calculated by method and 2, respectively, and n is the number of pairs of A and P being compared.
[b] % of total MSPE

In spite of the general agreement between methods, the more simple method 1, in which no data had to be discarded (as every single datum contributed to a category in a classificatory variable), was subsequently used for the analysis of lactation curves of milk and milk components. However, method 2, which is more suitable to simulate the effects of different lactation lengths (by changing t in equation 2 to a desired value), was used to analyse the effects of calving season on lactation length.

3.3. Lactation curves of autumn- and spring-calved cows (method 1)

Means across MOL for daily milk yields, fat and protein concentrations, and fat + protein yields for autumn- and spring-calved cows are shown in Fig. 2, 3, and 4, respectively. In MOL 1 to 4, daily yields of milk and milksolids were consistently greater for spring-calved cows than for autumn-calved cows, but in MOL 5 to 9 were consistently greater for autumn-calved cows. This resulted in a highly significant (P < 0.01) interaction between calving season and MOL. Lactation curves of all age groups within each herd (1st, 2nd, 3rd, and 4th or more lactations) followed the same general pattern as their respective herd's average, although milk yields of 1st lactation cows were generally lower than for the rest of the herd (Fig. 5).

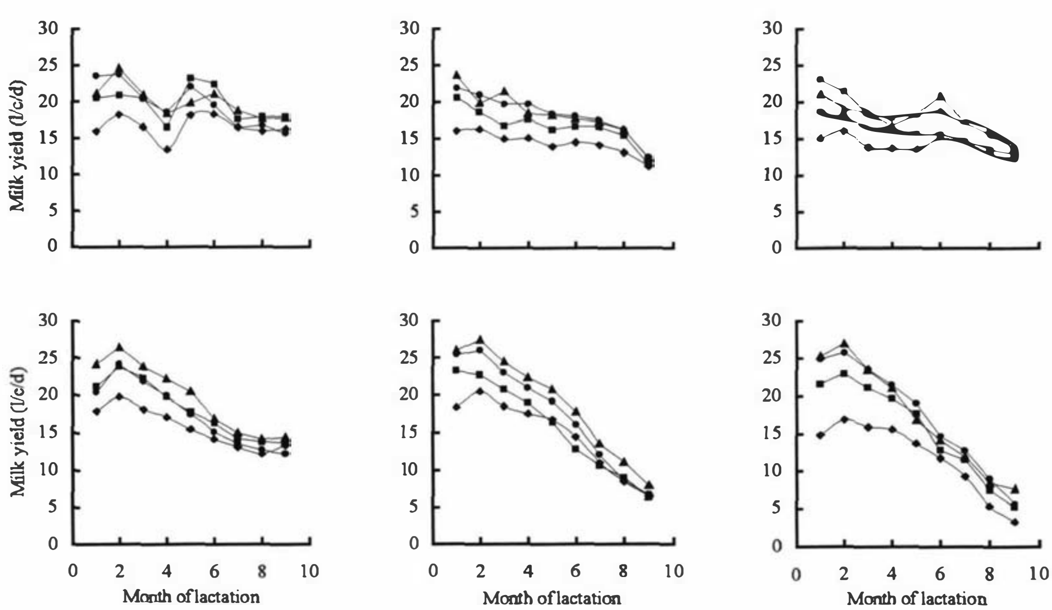
Fig. 4. Curves of daily milksolids yields (least square means, method 1) for autumn-(■) and spring-(▲) calved cows for Years 1 (left), 2 (middle), and 3 (right). Comparisons are between systems (100A vs 100S, top), and between herds within a system (50A vs 50S, bottom). Vertical bars represent standard errors of the least square means.



During MOL 1 to 4 in Years 1 and 2, the concentration of milk fat was higher, and that of milk protein was lower, for autumn-calved cows than for spring-calved cows (Fig. 3). In Year 3, milk fat concentration was higher for 100A than for 100S cows from MOL 2 to 7, but lower for MOL 1, 8 and 9, resulting in a significant interaction (P < 0.01) between calving season and MOL.

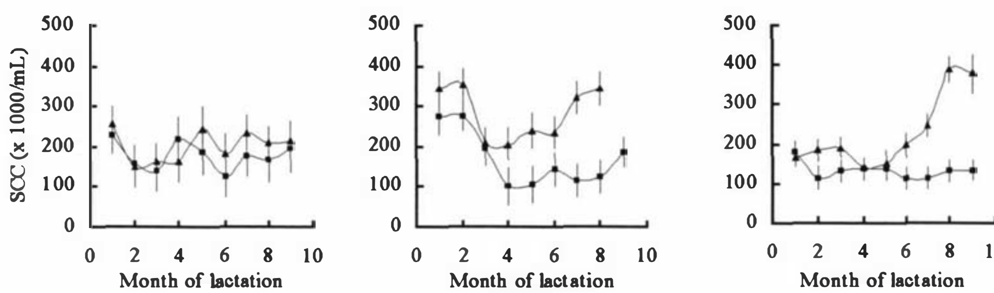
The general patterns showing relatively lower concentrations of solids in early lactation and higher concentrations in late lactation were more evident for milk protein than for milk fat. Consistently over the three years, the concentration of milk protein was higher for autumn-calved cows than for spring-calved cows between MOL 6 to 8, differences that were more accentuated during Years 2 and 3 (Fig. 3). Because of the patterns followed by concentrations of milk fat and milk protein, the interaction (time of the year × MOL) observed for the daily yields of milk fat + milk protein (milksolids) was stronger than for milk yield (Fig. 4). With the exception of Year 1, curves of milksolids yields for spring-calved cows did not show obvious peaks; instead, yields decreased continuously from their highest value at the start of lactation. These spring-calved cows, with the exception of Year 1, finished their lactation producing less than 0.7 kg milksolids/cow (Fig. 4), whereas autumn-calved cows finished their lactation with daily milksolids yields greater than 1.0 kg/cow in all the three years. The only exception was the abrupt decrease in daily milksolids yield observed for the 50A during Year 1 from 1.5 kg/cow in MOL 8, to slightly less than 1.0 kg/cow in MOL 9.

Fig. 5. Lactation curves of daily milk yield (least square means, method 1) for Years 1 (left), 2 (middle), and 3 (right) for 100A cows (top), and for 100S cows (bottom). Curves represent the averages for cows with 1 (◆), 2 (■), 3 (▲), and 4 or more (●) lactations.



Somatic cell counts were higher in mid and late lactation for the 100S cows than for the 100A cows in all the three years, although these differences were significant ($P < 0.05$) in Years 2 and 3, but not in Year 1 (Fig. 6). The same effect was observed in the comparison of the 50A and 50S herds within the 50/50 system in Year 2, although values were generally more variable.

Fig. 6. Curves of daily somatic cell count (least square means, method 1) for 100A (■) and 100S (▲) cows for Years 1 (left), 2 (middle), and 3 (right). Vertical bars represent standard errors of the least square means.



3.4. Analysis of phases of lactation (method 2)

A detailed analysis by herd and by year of phases 1 and 2 of the lactation curves is shown for milk yield in Table 3. With the exception of the 50A and 50S subherds in Year 1, the 305-d corrected total milk yields (l/cow) were greater for autumn-calved cows than for spring-calved cows, for the comparison carried out either between systems (100A vs 100S), between subherds within a system (50A vs 50S), or across systems ([100A + 50A] vs [100S + 50S]).

In general, a larger proportion of the total annual yield was contributed by the first phase of lactation for spring-calved cows (mean = 61%), and by the second phase of lactation for autumn-calved cows (mean = 62%). Lactation peaks of phase 1 were greater for 100S than for 100A cows, though these differences were significant ($P < 0.01$) for Years 1 and 3 only. However, lactation peaks of phase 2 were significantly higher ($P < 0.01$) for autumn-calved cows than for spring-calved cows in all three years. The time after calving to achieve peak yield of phase 1 was consistently shorter ($P < 0.01$) for 100A cows than for 100S cows (means across years = 27.1 and 42.2 days, respectively). The same difference was observed between the 50A and 50S herds, although it was significant only for Years 1 and 2.

3.5. Analysis of lactation length effect

Actual mean lactation lengths were consistently longer for autumn-calved cows in all the three years (Table 4). This occurred despite the fact that the same decision-guidelines (based on cows' body condition score and pasture availability) were applied on all the three systems, irrespective of their calving season.

Table 3 Milk yields (305-d corrected) and characteristics of phases 1 and 2 of lactation curves for autumn- and spring-calved cows in all three years.

	Herds					Contrasts[a]		
	100A	100S	50A	50S	SE	F	A	H
							P	
Year 1,								
Phase 1								
Peak yield (l/cow/d)	17.5	21.6	21.5	21.3	0.50	**	0.1	ns
Time to peak yield (d)	29	49	40	64	3.2	*	***	*
Cumulative yield (l/cow)	1453	3544	2498	3562	126	***	***	*
Phase 2								
Peak yield (l/cow/d)	18.5	9.5	18.3	11.7	0.63	***	***	**
Time to peak yield (d)	180	231	198	205	5.1	***	**	ns
Cumulative yield (l/cow)	3956	1439	3070	1759	141	***	***	**
Total milk yield (l/cow)	5409	4982	5567	5322	85.7	0.1	0.1	ns
Year 2								
Phase 1								
Peak yield (l/cow/d)	18.8	19.2	18.9	18.3	0.44	ns	ns	ns
Time to peak yield (d)	29	40	23	34	2.3	*	0.1	ns
Cumulative yield (l/cow)	2472	2550	2045	1838	104	ns	ns	ns
Phase 2								
Peak yield (l/cow/d)	13.8	10.0	16.5	13.4	0.61	**	*	ns
Time to peak yield (d)	199	163	195	152	3.9	***	***	*
Cumulative yield (l/cow)	2434	1762	3387	2478	127	*	*	ns
Total milk yield (l/cow)	4906	4311	5432	4316	76.3	***	***	**
Year 3								
Phase 1								
Peak yield (l/cow/d)	17.8	20.2	19.3	19.9	0.44	*	ns	ns
Time to peak yield (d)	23	38	59	33	2.1	**	ns	**
Cumulative yield (l/cow)	1612	2739	1984	2773	120	***	**	ns
Phase 2								
Peak yield (l/cow/d)	15.1	9.3	13.0	7.7	0.66	***	**	0.1
Time to peak yield (d)	194	156	200	156	4.8	**	ns	**
Cumulative yield (l/cow)	3269	1489	2691	1268	133	***	***	*
Total milk yield (l/cow)	4880	4228	4675	4042	75.3	***	***	0.1

[a] F = between farms (100A vs 100S); A = all cows ([100A + 50A] vs [100S + 50S]); H = between herds within a farm (50A vs 50S)
* $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$; ns = not significant ($P > 0.1$)

The predictive ability of method 2 was tested by comparing the average total yields predicted by the method with the actual total milk production per system measured on the farms (Table 4). This was done to ensure that any further extrapolation of the data (to evaluate the effect of lactation length) would be based on a lactation curve model that could provide reliable estimates of the actual total yields. Actual values were obtained by dividing the weighted total daily milk yields produced by each herd by the number of cows, and predicted values were calculated using the actual herds' lactation lengths for each year as inputs for the diphasic equation. For the split-calving system, actual values were compared with the prediction for both the 50A and 50S subherds. In Year 1, the difference between actual and predicted values, expressed as a percentage of the actual values, was smaller than 10 % for both the 100A and 100S systems, although it was nearly 20 % for the 50/50 system. In contrast to Year 1, actual and predicted values in the three systems differed by less than 4.2 % in Year 2, and by less than 1 % in Year 3 (Table 4).

Table 4. Predicted and actual values of total milk yield per cow for each herd and each year.

Year	Herd	Actual lactation length (d)	Whole-lactation milk yield (l/cow)			Difference
			Predicted (P)[a]	$SE_{(p)}$[b]	Actual (A)[c]	[P-A]/A (%)
	100A	281	5162	150	4730	9.1
	100S	258	4572	132	4285	6.7
1	50A	284	5391	161	...	...
	50S	268	4922	197	...	...
	50/50	276	5158	...	4309	19.7
	100A	298	4851	118	4810	0.8
	100S	239	3980	106	4045	-1.6
2	50A	278	5144	248	...	...
	50S	233	3950	223	...	...
	50/50	255	4547	...	4361	4.2
	100A	296	4796	142	4759	0.8
	100S	226	3870	89	3907	-0.9
3	50A	276	4372	244	...	...
	50S	201	3463	168	...	...
	50/50	239	3918	...	3942	-0.6

[a] Predicted values are calculated using the respective actual lactation lengths as inputs for equation (2)
[b] Standard error of the predicted value
[c] Actual values are calculated as total herd annual yield divided by the total number of cows in each herd. Because both 50A and 50S herds were managed as one herd, only the actual production for the whole system (i.e. 50/50) can be calculated in this way.

Based on the general agreement between actual and predicted values, it was possible to estimate the extent to which the higher total milk yield by the 100A cows was due to the achievement of longer lactation lengths, or to the higher daily milk yields in mid and late lactation (seasonal effect). This was done by extending the lactation lengths of the 100S cows in the model (equation 2) to the same lengths achieved by the 100A cows for each year, and comparing the actual differences in milk yield between the two herds, with the differences between the predicted yields using the same lactation lengths for both herds (i.e., those achieved by the 100A cows). Results in Table 5 show that the greatest proportion (70 % to 83 %) of the total differences in milk yield between 100A and 100S cows was due to greater yields in late lactation by the 100A cows, with only 17 % to 30 % of the difference due to their longer lactations.

Table 5. Actual and estimated differences in total milk yield per cow between 100A and 100S cows, and partition of the causes (days in milk and seasonal) of those differences.

Year	Differences (100A – 100S) in milk yield (l/cow)		Partition of effects (% of total difference)	
	Actual[a]	Estimated[b]	DIM[c]	Season[d]
1	444	367	17	83
2	765	564	26	74
3	852	592	30	70

[a] Measured by weighing each herd's total production daily
[b] Lactation yields estimated using the diphasic model (equation 2), but including the actual average of lactation length achieved by the 100A cows as input for both herds
[c] Effect due to extra days in milk, calculated as [1-(Estimated/Actual) × 100]
[d] Effect due to season of the year, calculated as [(Estimated/Actual) × 100]

4. Discussion

4.1. Linear- and non-linear-based methods

Lactation curves obtained by method 2 were in relatively good agreement (Fig. 2) with those obtained by method 1, despite the very contrasting shapes of the lactation curves of autumn- and spring-calved cows, and despite the loss of more than 50 % of the original data in method 2. This is in agreement with results from a previous study (Scott *et al.* 1996), although the use of the diphasic equation has been criticised because of the difficulties associated with the justification of the lactation process as a multiphasic process (Tozer and Huffaker, 1999).

Method 2 resulted in a slight overprediction of milk yields for autumn-calved cows, and a slight underprediction for spring-calved cows (see Fig. 2), but the overall MPE between predicted values (method 2) and actual values (method 1) was in most cases within the range considered as satisfactory (≤ 10 %). In the other two cases, MPE was lower than 11 %, which is still within the 'acceptable' range (Table 2). Values for MPE were greater for both the 50A and the 50S subherds, due probably to the smaller numbers of cows than in the 100A and 100S systems. Further, total lactation yields predicted by method 2 were in close agreement with actual values (Table 4), particularly for Years 2 and 3 in which individual milk yields were measured more frequently.

The major advantages of non-linear methods, such as method 2, lie in their ability to fit lactation curves to the yield data of individual cows and then to describe parametrically the resulting curves. However, in order to fully utilise these advantages when studying lactation curves of individual grazing cows (which can vary widely in shape), manipulation of data (e.g. by interpolation or smoothing) prior to fitting the model might help to improve model convergence. However, none of these manipulative alternatives were used in the present study.

4.2. Calving season

Strong interactions were observed between the effects of calving season and MOL, for yields of milk and milk solids, and for concentrations of milk fat and protein. For the autumn-calved cows, their lower yields at peak of lactation were compensated by higher yields in mid and late lactation, and by longer lactations, when compared with spring-calved cows. Autumn-calved cows gained body condition during the latter phase of lactation (see Appendix), a reflection of the pasture availability in spring, whereas the spring-calved cows did not gain condition in this phase (late summer-early autumn). These effects were observed in the present study not only for comparisons between systems (100A vs 100S, which differed in their stocking rates), but also for comparisons between herds within a system (50A vs 50S, which were stocked at the same rate), suggesting that the effect was independent of the stocking rate. These results are in general agreement with previous studies (Thomas *et al.* 1985; Auldist *et al.* 1997; Olesen *et al.* 1999; Ryan, 1999).

The interactions between the effects of calving season and MOL on concentrations of milk fat and milk protein (Fig. 3), are in general agreement with previous studies (Auldist *et al.* 1998; Ryan, 1999), and can be partially explained by changes in the availability and quality of feed. High quality pasture in springtime (Table 1), when all cows were fed on grazed pasture only, was always associated with relatively higher concentrations of milk protein, either in early lactation for spring-calved cows, or in mid to late lactation for autumn-calved cows (Fig. 3). In contrast, for most of the autumn-calved cows, MOL 2 (30 to 60 days in milk) coincided with late autumn and early winter, when they were supplemented with relatively large amounts of maize silage (6-9 kg DM/cow daily) in all the three years. This resulted in a lower ME concentration in the diet of cows (see Table 1).

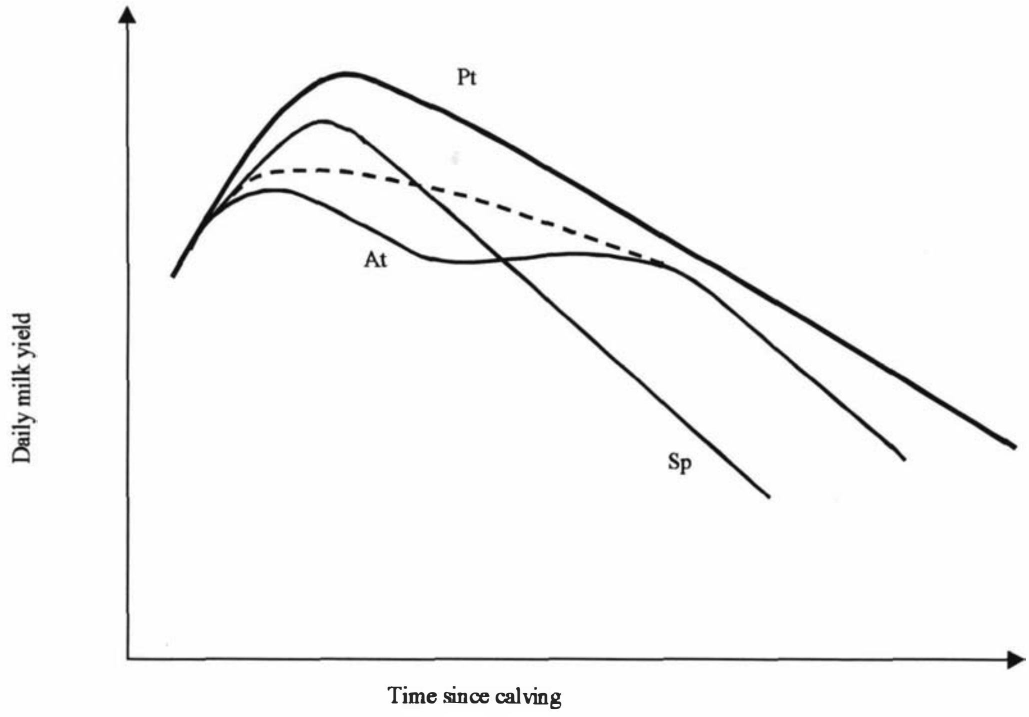
Similarly, the concentrations of protein in the milk of spring-calved cows in late lactation (MOL 6-7) did not decrease during the wet summer of Year 1, but decreased considerably during the dry summers of Years 2 and 3 (Fig. 3). This effect was likely due to the lower overall nutritive value of pasture in the summers of Years 2 and 3 (Table 1), together with the relatively larger quantities of grass silage fed to the cows (4.7 and 7.7 kg DM/cow/day for Year 2 and 3, respectively) during those summers as a consequence of severe soil moisture deficits. In agreement with this, Ryan (1999) reported that the 100 % autumn calving system had the lowest milk protein concentration at the end of lactation, when cows were being offered grass silage indoors.

The higher SCC in late lactation observed for the 100S cows than for the 100A cows in Years 2 and 3 (Fig. 6) may be the result of a 'dilution' effect (Lacy-Hulbert *et al.* 1995), rather than a direct 'calving season' effect. This is supported by the fact that during the wetter summer of Year 1, in which the nutritive value of the pasture was higher than in the other two years (Table 1), daily milk yields of spring-calved cows were comparatively higher than in Years 2 and 3, and differences in SCC in late lactation between autumn- and spring-calved cows were smaller and not significant (Fig. 6).

Autumn-calved cows had greater total lactation yields than spring-calved cows, due to both longer lactations (Table 4) and greater milk yield in mid and late lactation (Fig, 2-3 and Table 3). The effect persisted after correcting the lactation lengths to 305 days (Table 3), which agrees with previous studies (Thomas *et al.* 1985; Ryan *et al.* 1997). Further, data extrapolation using the diphasic equation suggests that even if the spring-calved cows had achieved the same lactation lengths as those achieved by the autumn-calved cows, the difference in total milk yield between the two groups of cows would have been reduced only by about 25%, with the other 75% of the difference explained by greater yields in mid and late lactation. However, caution is required in interpreting these results due to the large numbers of records discarded for method 2.

A hypothetical explanation of the observed differences in the shape of the lactation curve of autumn- and spring-calved cows is shown in Fig. 7. Compared with indoor-fed cows offered total mixed rations *ad libitum* (potential yield, "Pt"), spring calving cows in pasture-based systems (curve "Sp") are limited by nutritional factors to the extent represented by the area between the two curves. Differences are smaller around early lactation (spring) when cows are fully fed on high quality pasture (Tables 1 and 2), but they are enlarged as lactation progresses into the summer-autumn period. This is supported by recent work carried out in New Zealand in which heifers of two genetic lines fed total mixed rations outperformed their counterparts fully fed on pasture (Kolver *et al.* 2000).

Fig. 7. A hypothetical explanation of the differences between lactation curves of cows calving in the autumn (At), or spring (Sp) in pasture-based systems, in which both groups of cows are prevented from achieving the potential yield (Pt). The broken line represents the theoretical lactation curve of autumn-calved cows fully fed throughout lactation.



In contrast, autumn-calved cows (curve "At") are more limited in early lactation, probably due partly to nutritional factors (represented in Fig. 7 by the area between the broken line and the curve At) and partly to climate factors (mainly photoperiod, see review by Dahl *et al.* (2000)), indicating that a lower peak yield for autumn- than for spring-calved cows is unavoidable even if the cows are well fed. These non-nutritional limiting factors are represented in Fig. 7 by the area delimited by the broken line and the lactation peak of the Sp curve, although the relative importance of these climate-related factors may be greater in sub-tropical rather than in temperate regions (García and Holmes, 1999).

5. Conclusion

Similar average results were obtained by method 1, based on test-day analysis, and method 2, based on the multiphasic equation of Grossman and Koops (1988), despite the deletion of data from the latter. In these pasture-based systems, lactation curves of autumn-calved cows differed significantly in shape and in total yields of milk and milksolids from those more typically shaped curves of the spring-calved cows. This effect was partially due to longer lactations, but also, and apparently more importantly, to greater daily yields in mid and late lactation by the autumn-calved cows, indicating that maximising peak yields in early lactation of cows may not be as important in pasture-based systems as it is for other production systems. The availability of quality pasture in spring was positively associated with relatively higher concentrations of milk protein for both autumn- and spring-calved cows. These differences in total yield of milk and milksolids, and also in SCC, could have important implications for the New Zealand dairy industry if a significant proportion of cows were calved in the autumn. Similar quantities of milk could be produced with fewer cows (greater yields by autumn-calved cows), the installed industry facilities could be utilised more fully by processing more milk during winter, and the relatively lower quality of milk in the autumn (high SCC) could be improved by mixing it with milk from autumn-calved cows in early lactation.

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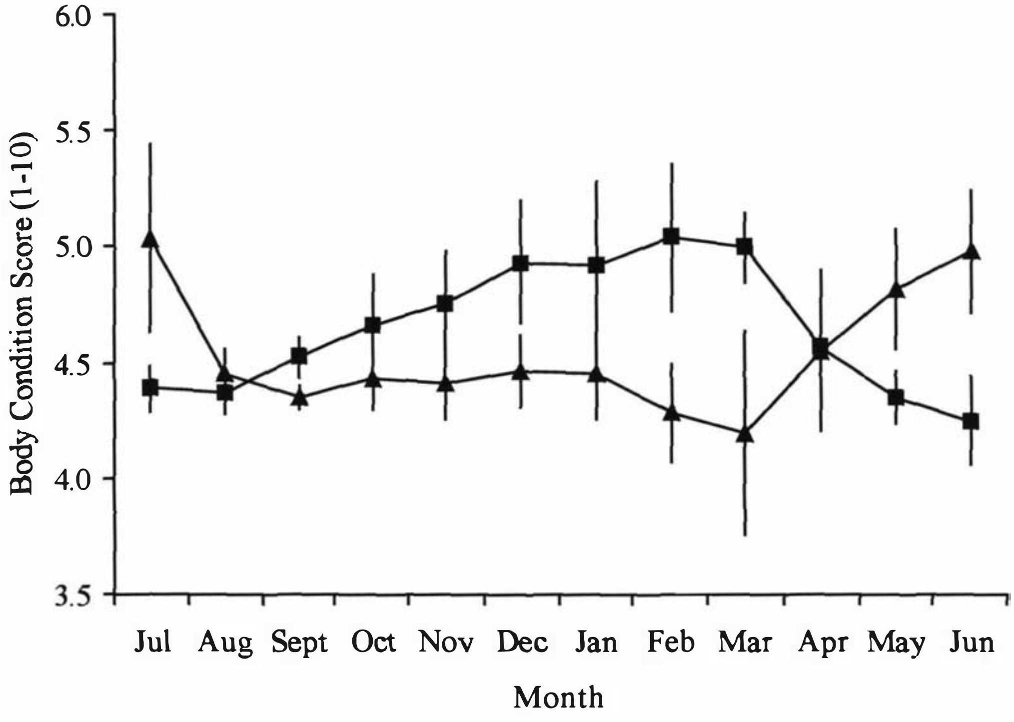
Appendix

Monthly values for body condition score (scale 1-10) for cows that calved in the autumn (■) or in the spring (▲), averaged across all 3 years.



Overview of Chapter 4

In Part I, the central hypothesis regarding the overall performance of contrasting calving systems has been identified (Chapter 1), and tested at the whole system level (Chapter 2). In addition, some of the key components involved in the performance of these systems, i.e., the lactation curves and milk yields by individual cows, have been dealt with in more detail in Chapter 3. Overall, the main outcome of Part I has been the finding that very contrasting calving systems can perform similarly in terms of physical production (Chapter 2), and that the differences in the lactation curves between autumn- and spring-calved cows is a key determinant of that performance (Chapter 3).

However, in order to be able to fully compare the efficiencies of different calving systems, knowledge of the quantities of feed eaten by the cows is crucial. The studies on the DM intake, together with some evaluation of methodologies are dealt with in Part II.

In these pasture-based systems, herbage DM intakes can be estimated by different methods, a topic covered in Chapter 5, but no methodologies have been developed to "measure" (or more correctly, "estimate") intakes of herbage and maize silage by individual grazing cows being offered the supplement as a group. For systems that utilise significant quantities of this forage, as is the case for the winter-milk production systems in New Zealand, this is of vital importance, and the acquisition of such methodology might have important implications not only for the present but also for future systems experiments. The following chapter, Chapter 4, covers this topic.

Part II

Specific Studies

Chapter 4

The combination of the n-alkanes and ^{13}C techniques to estimate individual dry matter intakes of herbage and maize silage by grazing dairy cows

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Abstract. Two studies were conducted at Massey University in 1998. Experiment 1 investigated the combined use of n-alkanes and ^{13}C techniques for the estimation of individual proportions and total intakes of herbage (H) and maize silage (MS) by dairy cows. Experiment 2 measured the variation in the amount of MS consumed by individual cows fed as a group. In Experiment 1, 6 dry Holstein-Friesian cows were kept indoors and fed a diet containing one of the following H:MS ratios (dry matter basis): 100:0, 80:20, 60:40, 40:60, 20:80 or 10:90 for 25 days. Cows were dosed with a slow-release capsule containing 8 g of dotriacontane (C_{32}) and 8 g of hexatriacontane (C_{36}). Intake estimates were based on individual faecal samples collected twice daily during two 5-day periods. In Experiment 2 (grazing trial), 12 early-lactation cows were selected from a commercial herd of 48 autumn-calving cows and blocked into pairs according to milk yield, lactation length and lactation number in a complete block randomised design. Within each pair, cows were randomly assigned to two treatments: supplemented, S (4 kg MS DM per cow after the morning milking in feed troughs) or not supplemented, NS. Another 8 cows were randomly selected from the rest of the herd to increase the number of individual estimations of H and MS intakes. Cows grazed perennial ryegrass-white clover pasture during the rest of the day. In Experiment 1, H:MS ratios were not accurately predicted by the odd-chained n-alkanes, but there was a strong linear relationship between the concentration of ^{13}C in faeces and actual H:MS ratios in the diet. The ^{13}C method was therefore combined with the n-alkanes, resulting in accurate estimations of H and MS intakes. In Experiment 2, a large variation was observed among individual cows in their daily intakes of MS (range 0.94 to 5.09 kg DM per cow, coefficient of variation = 36 %), but this variation in MS intake was not associated with milk yield ($P > 0.05$). The results indicate that the n-alkane and ^{13}C techniques can be successfully combined to estimate the intakes of MS and H by grazing cows supplemented as a group. Under the conditions of the present study, individual cows differ considerably in the amount of maize silage consumed per day, although the reasons for this are not clear.

Keywords: n-alkanes; ^{13}C; dry matter intake; herbage; maize silage

1. Introduction

Research on the effects of maize silage as supplementary feed for grazing dairy cows under commercial farm conditions is constrained by a lack of an adequate methodology for estimating individual intakes of herbage and supplements by grazing dairy cows. Maize silage is a common supplementary feed for grazing dairy cows in New Zealand and other temperate regions of the world, particularly for autumn-calving systems in which it can account for up to 50% of the cows' total dry matter (DM) intake during winter. When grazing dairy cows are supplemented with maize silage fed in troughs or directly in the paddocks, individual cows can consume variable quantities of the supplement, making it difficult to predict the supplement's nutritional and financial effects. Wide variation in intake of supplements between individuals has been earlier reported for grazing sheep supplemented with concentrate as a group (Curtis *et al.* 1994; Holst *et al.* 1994). However, no similar information is available for grazing dairy cows being supplemented with maize silage.

Herbage DM intake of grazing animals can be accurately estimated by the n-alkanes method (Mayes *et al.* 1986 *a*; Dillon and Stakelum 1989; Reeves *et al.* 1996; Robaina *et al.* 1997). The method also allows the estimated intake of herbage to be corrected when grazing animals are given supplements, providing that both the alkanes profile of the supplement and the amount of supplement eaten by each individual animal are known (Dove and Mayes 1991). Moreover, if the n-alkanes profile of the supplement is sufficiently different from that of the pasture, the proportion of each component in the individual diet can be estimated, even when the grazing cows are being given the supplement as a group (Dove and Mayes 1996). Despite the fact that the low concentrations of n-alkanes in the maize plant (Bianchi and Avato 1984) would suggest that this approach cannot be used for maize silage, the method has not been tested with diets containing different proportions of herbage and maize silage.

The ^{13}C method, which takes advantage of the different concentrations of the stable isotope ^{13}C between tropical-season (C_4 photosynthetic pathway) and cool-season plants (C_3 photosynthetic pathway; see Farquhar *et al.* 1989), has been used to differentiate between intake ratios of C_3 and C_4 plants (Jones *et al.* 1979; Coates *et al.* 1993). However, the method has not been utilised to estimate diet composition when dairy cattle graze temperate pasture and receive maize silage as supplementary feed.

Two experiments were carried out in the present study. Experiment 1 (indoor trial) tested the hypothesis that either the n-alkanes method alone, or the combination of ^{13}C method (to estimate herbage : silage ratios) and n-alkanes (to estimate the intake of herbage DM) could be used to accurately predict the proportions and total amounts of maize silage and herbage DM consumed by individual grazing cows. This was carried out by comparing the predictions of each method against weighed amounts of different proportions of herbage and maize silage DM consumed by dairy cows. In Experiment 2 (grazing trial) the validated methodology was utilised to study the variation of herbage and maize silage DM intakes among individual cows under commercial farm conditions.

2. Materials and Methods

2.1. Experiment 1

Six Holstein-Friesian, non-lactating cows (549 ± 56 kg liveweight) were randomly assigned to diets containing approximately (DM basis) 100:0, 80:20, 60:40, 40:60, 20:80 or 10:90 of predominantly perennial ryegrass (*Lolium perenne*)-white clover (*Trifolium repens*) pasture and maize silage (*Zea maize*) for a period of 25 days. Cows were maintained in individual stalls with *ad libitum* access to fresh water. All cows were fed once daily at 09.00, at approximately 1.3 × maintenance (Holmes *et al.* 1987). The animals had been grazing on pasture until the experiment began, thus diets containing more than 40% maize silage were gradually introduced during days 0 to 10.

Pasture herbage was cut every morning, weighed and offered to the cows in individual bins. Immediately after the herbage had been given, the corresponding allocations of fresh maize silage were weighed and offered in separate bins. The maize silage was taken every 3 or 4 days from a stack and stored at below 10 °C until required for feeding. On each day of the experimental period, three samples of each forage were air-dried overnight at 100 °C to determine the concentration of DM. Any residue left after 24 h was weighed and a sample air-dried overnight at 100 °C to determine the concentration of DM.

From days 12 to 17 and 19 to 24, a representative sample of each forage was taken daily at feeding time, and frozen. Later, two composite samples (one per period) were created by pooling the daily sub-samples of each forage. Samples were kept at −17 °C until analysed.

On day 6, cows were dosed with a controlled release device capsule containing 8 g of dotriacontane (C_{32}) and 8 g of hexatriacontane (C_{36}) (Captec™, New Zealand) with a constant release rate for each n-alkane of approximately 400 mg per day. Faecal samples were taken twice daily (0800 h and 1600 h) from each individual cow by rectal grab-sampling during two 5-day periods (days 13 to 18 and 20 to 25). A composite sample was created by adding (wet basis) a new sub-sample to a pool (one per cow and per period) immediately after taking the samples. Thus, two composite samples (each containing morning and afternoon sub-samples of 5 consecutive days) were analysed for each individual cow.

Faecal, herbage and maize silage composite samples were thawed, freeze-dried and ground in a mill (1 mm screen). Samples were then analysed to determine concentrations of n-alkanes (Mayes *et al.* 1986 *a*) by gas chromatography (Model 5890 A, Hewlett-Packard, Avondale, P.A.) and of the stable isotope ^{13}C by mass spectrometry (Europa Scientific Tracermass). The concentration of ^{13}C is normally given as $\delta^{13}C$, i.e. the proportions of ^{13}C and ^{12}C relative to a carbonate standard (Farquhar *et al.* 1989). Herbage and maize silage samples were also analysed for organic matter (OM), neutral detergent fibre (Robertson and Van Soest 1981), *in vitro* digestibility of DM and OM (Roughan and Holland 1977) and nitrogen by Kjeldahl procedure.

Intakes of herbage DM were calculated according to the formula of Dove and Mayes (1991), which includes the amount of supplement consumed. Tritiacontane (C_{33}) was used as the naturally-occurring alkane and C_{32} as the dosed alkane.

The proportions of herbage and maize silage were estimated using two calculation methods. In method 1 the odd-chained n-alkanes (C_{27}-C_{35}) were used following the procedure described by Dove and Moore (1995) and assuming faecal recovery rates of Mayes *et al.* (1986 *b*). In method 2 the proportions of herbage and maize silage OM ratios in the faeces were estimated by solving the following linear equation for each value of faecal $\delta^{13}C$:

$$(H \times \delta^{13}C_{herbage}) + (MS \times \delta^{13}C_{maize\ silage}) = \delta^{13}C_{faeces}$$

where H and MS are the unknown proportions (constrained to vary between 0 and 1) of herbage and maize silage OM, respectively. Because mass spectrometric determinations are made on a carbon basis, results were adjusted for ash contents of each forage and expressed as proportions of faecal DM (Jones *et al.* 1979). The values of faecal DM ratios were then combined with the amount of faecal output (FO) derived from herbage (calculated from herbage intakes values and the $IVOMD_{herbage}$) to calculate total FO. Faecal output derived from maize silage was therefore calculated as the difference between total FO and the estimated faecal output derived from herbage. Maize silage intakes (kg DM per cow per day) were then calculated by the equation:

$$\text{Maize silage intake} = FO_{maize\ silage} / (1 - IVOMD_{maize\ silage})$$

The procedure described is a combination of both the n-alkanes and $\delta^{13}C$ methods. Thus, the estimate of maize silage intake depends on the estimate of herbage intake (for calculation of total FO) while the latter must be corrected for the amount of supplement consumed, resulting in a circular relation between the two equations. Therefore, both formulas were allowed to re-correct each other in an iterative way until a further correction resulted in a negligible change (< 0.001 kg) in the predicted intake of herbage and maize silage.

The accuracy of the methods was evaluated by simple linear regression analyses of actual versus estimated values. In addition, mean square prediction error values (MSPE) were calculated for each variable analysed:

$$MSPE = \sum (A - P)^2 / n$$

where A is the actual mean intake, P is the predicted mean intake and n is the number of pairs of A and P values being compared (Bibby and Toutenburg, 1977). The MSPE was selected because it represents the sum of three components, which account for mean bias, line bias, and random variation about the regression line (Roseler *et al.* 1997). In order to facilitate interpretation of results, error values are presented as the square root of the MSPE, designated as mean prediction error (MPE), expressed as a percentage of the mean actual intake for each variable.

2.2. Experiment 2

The experiment was conducted at N° 1 Dairy Farm, Massey University during May and June, 1998. The farm was being used for a large experiment involving three systems in which cows calve at different times of the year (García *et al.* 1998; see also Chapter 2). A herd of 48 Holstein-Friesian lactating cows, which had calved between 24 March and 23 April was used for the experimental work. The herd was being fed with a daily target of 4 kg DM per cow of maize silage in troughs (1.5 linear m per cow) for approximately 2 hours after the morning milking; the herd then grazed pasture during the rest of the day. Twelve cows (4 primiparous and 8 multiparous) were selected from the herd and blocked into pairs according to level of milk yield, days since calving and lactation number. Cows within each block were randomly assigned to one of two treatments: supplemented (S) or not-supplemented with maize silage (NS). The latter treatment involved separating the 6 NS cows from the rest of the herd during the period of silage feeding after the morning milking. Another 8 cows were randomly selected from the rest of the herd in order to increase the number of individual estimates of herbage and maize silage intakes. Thus, 14 cows (6 paired and 8 not paired) received the same feeding treatment (S) as the whole herd (pasture + maize silage), while 6 cows were allowed to consume only grazed pasture (NS).

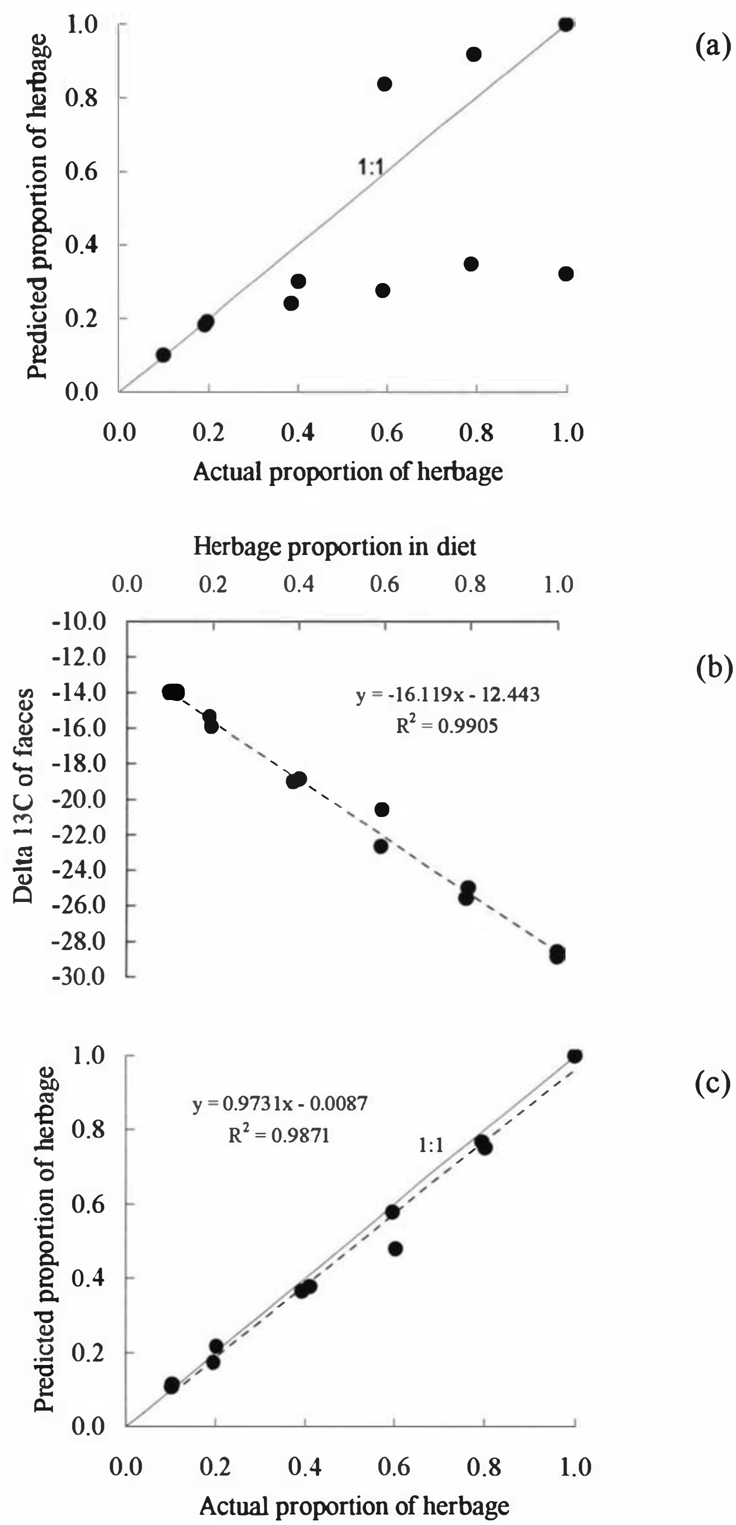
Pastures comprised mainly perennial ryegrass (> 70 %) and white clover, and were offered at an average daily allowance of 28.9 ± 2.5 kg DM per cow during the whole experimental period. Pre and post-grazing herbage masses were estimated for all the paddocks grazed during the experimental period from 100 readings of pasture height using a rising plate meter (Michell, 1982). Fifteen "exclosure" cages (1 m x 0.5 m x 0.5 m) were distributed on each paddock before grazing. Approximately 30 sub-samples were taken by 'hand-plucking' from each cage after each grazing, in order to accurately represent the actual material grazed. Herbage samples were first pooled by paddock and then by sampling period, resulting eventually in two composite samples being chemically analysed (one for each 5-day period).

Maize silage was weighed daily on a wet basis using the load-cells of the forage-wagon, according to the average targeted DM intake. Samples of silage were taken daily from the bins, oven-dried at 60 °C for 48 h and the DM content (and total actual DM offered) was calculated for each experimental day. All sub-samples were later pooled into one sample for each 5-day period. The accumulated residue of uneaten silage was collected and weighed at the end of each sampling period. A sample was taken and oven dried (60 °C, 48 h) to calculate the DM content. The average consumption of maize silage by the whole herd was calculated as the difference between the total amounts of DM offered and refused during each period.

The dosing with n-alkanes, faecal sampling procedure and chemical analyses on all samples were identical to those described for Experiment 1, except that faecal samples were collected from the ground in the field.

Grazing behaviour was recorded by observing the cows over two 24-h periods (days 9 and 16). Individual cows were observed every 10 m and their activities were recorded either as grazing, ruminating or idling. The behavioural measurements were part of another study (L. Watson, unpublished), thus only main results are mentioned here when appropriate.

Fig. 1. (a) Prediction of the proportions of herbage in the diets of cows by using the odd-chained n-alkanes in the feeds and in the faeces. (b) The relationship between proportions of herbage (C_3) in the diet and the $\delta^{13}C$ in the faeces. (c) Prediction of the proportions of herbage in the diets of cows by the combination of n-alkanes and $\delta^{13}C$ techniques. Solid lines indicate x = y equation. Dashed lines indicate fitted regression equations.



Values for DM intake were analysed as a complete randomised block design using the statistical software SAS (1990). Mean values were considered to be significantly different when $P < 0.05$. Means for the whole set of 14 experimental (supplemented) cows are also presented when appropriate. Regression analyses were performed between the mean values of herbage, maize silage and total DM intake and the level of milk yield.

3. Results

The chemical composition of the forages utilised for each experiment is shown in Table 1. Differences in quality between the two pastures were mainly a consequence of the times of the year when the pastures were utilised (late spring for Experiment 1 and autumn-winter for Experiment 2). The concentrations of dominant n-alkanes were 12-15 times higher in the pastures than in the maize silage for both experiments. Despite these differences in chemical composition, the concentration of ^{13}C for each forage was remarkably similar between experiments.

Table 1. Chemical composition, concentration of dominant n-alkanes and concentration of ^{13}C in the forages utilised for Experiments 1 and 2. Standard deviation values are given below each mean value.

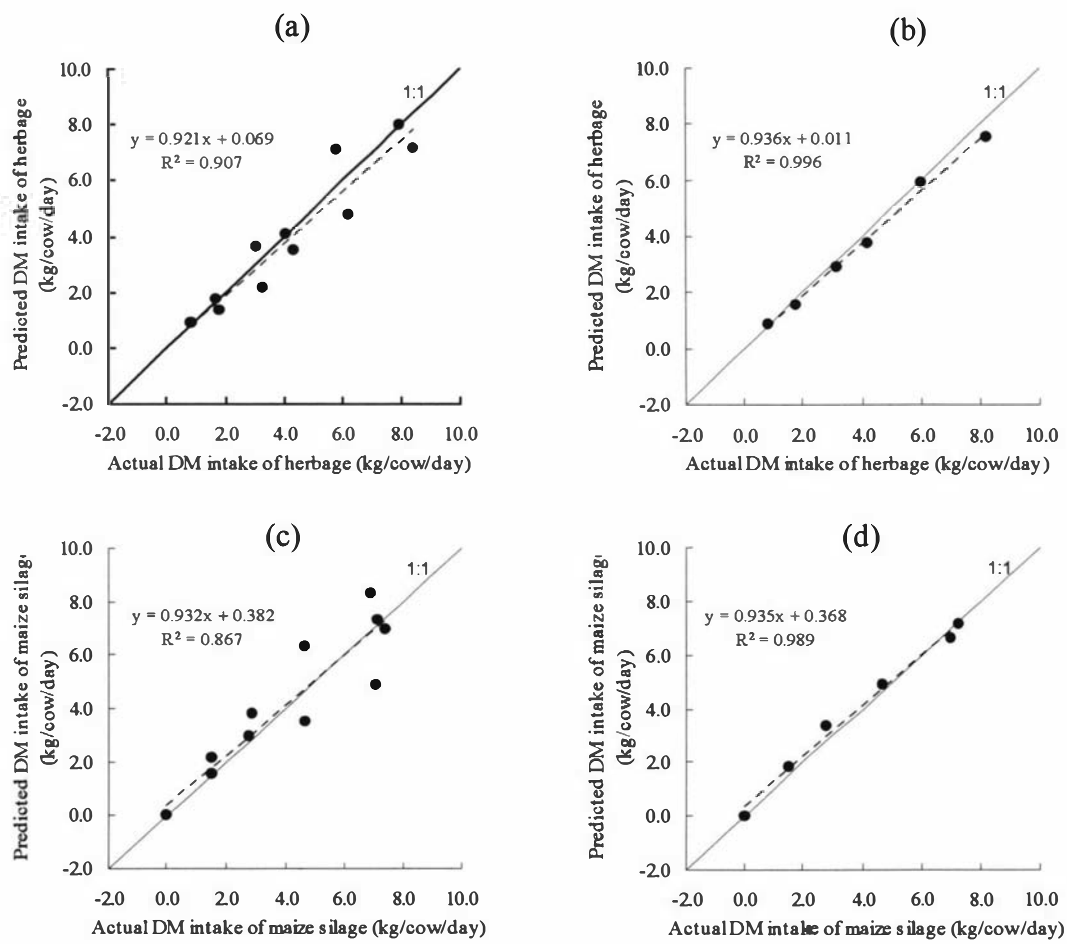
		DM*	OM	CP	IVOMD	NDF	C_{29}	C_{31}	C_{33}	$\delta^{13}C$
Exp.	Forage	g/100 g DM					mg/100 g DM			‰
	Herbage	21.0	92.9	10.5	69.2	52.1	14.9	29.3	7.95	-28.7
		3.21	0.60	1.55	2.74	2.55	2.89	4.77	1.35	0.20
1	Maize silage	34.4	96.2	7.9	76.1	37.1	1.01	1.35	0.98	-11.7
		1.12	0.35	0.31	1.52	3.30	0.10	0.20	0.10	0.06
	Herbage	14.0	88.4	26.3	74.1	39.8	6.9	13.4	12.6	-29.9
		0.52	0.40	2.15	1.21	0.70	1.17	2.61	2.03	0.12
2	Maize silage	30.1	94.3	7.2	65.4	48.6	1.10	0.77	1.00	-11.5
		0.10	0.09	0.20	0.57	0.38	0.02	1.10	0.05	0.10

*DM = dry matter; OM = organic matter; CP = crude protein; IVOMD = *in vitro* OM digestibility; NDF = neutral detergent fibre; C_{29} = nonacosane; C_{31} = hentriacontane; C_{33} = tritriacontane; $\delta^{13}C$ = abundance of ^{13}C relative to a carbonate standard.

3.1. Validation trial (Experiment 1)

The n-alkanes method alone (method 1) did not result in adequate predictions of the proportions of each feed component in the diet (MPE = 52.3 %), except for the two diets that contained the lowest proportions of herbage (20:80 and 10:90, Figure 1 *a*). Conversely, $\delta^{13}C$ values in faeces (method 2) were strongly correlated to the percentages of herbage in the diet (Figure 1 *b*), which resulted in the actual ratios of herbage:maize silage being accurately predicted by $\delta^{13}C$ (MPE = 8.3 %) after correction for OM content of each forage (Figure 1 *c*). Consequently, the $\delta^{13}C$ method was combined with the n-alkanes method to estimate individual DM intakes of herbage and maize silage as previously described. The combined methodology is thereafter referred to as *Alkane & ^{13}C*.

Fig. 2. Predicted (*Alkane & ^{13}C*) versus actual intakes of herbage and maize silage. (a) and (c), using all individual values for each cow and for each experimental period. (b) and (d), using the average of two experimental periods for each cow. Solid lines indicate x = y equation. Dashed lines indicate fitted regression equations.



The individual amounts of herbage and maize silage DM intake predicted by the Alkane & ^{13}C methodology were in good agreement with the actual amounts eaten (Figure 2 *a* and *c*), although actual herbage DM intake was predicted with slightly higher accuracy than was maize silage DM intake (MPE = 19.9 % and 26.1 %, respectively). In both cases, however, over 90 % of the total MSPE was due to random variation, which was partially removed (MPE = 8.2 % and 8.8 %, respectively) after averaging the intakes values of the two periods for each cow (Figure 2 *b* and *d*).

3.2. Grazing trial (Experiment 2)

Averaged across the two experimental periods, the S and the NS cows ate similar amounts of herbage ($P > 0.05$), which resulted in a large additive effect of the supplement on the total daily DM intake (Table 2). Supplemented cows consumed on average 2.60 (6 paired S cows, SE = 0.47) or 2.94 (all 14 S cows; SE = 0.35) kg DM of maize silage per day compared with virtually zero for the NS cows ($P < 0.01$), as estimated by the Alkane & ^{13}C method. These figures were respectively, 32 and 23 % lower than the mean intake for the whole herd calculated by weighing the silage offered and refused (Table 2). Similarly, the average herbage DM intake estimated by the Alkane & ^{13}C method was 9 % lower than the mean for the whole herd calculated by the differences between herbage mass present before and after each grazing (Table 2). The large additive effect of the supplement resulted in a significant difference ($P < 0.05$) in total daily DM intake between the S and the NS cows (Table 2). Consequently, substitution rate (kg of herbage intake reduction per kg of maize silage consumed) was only 0.08.

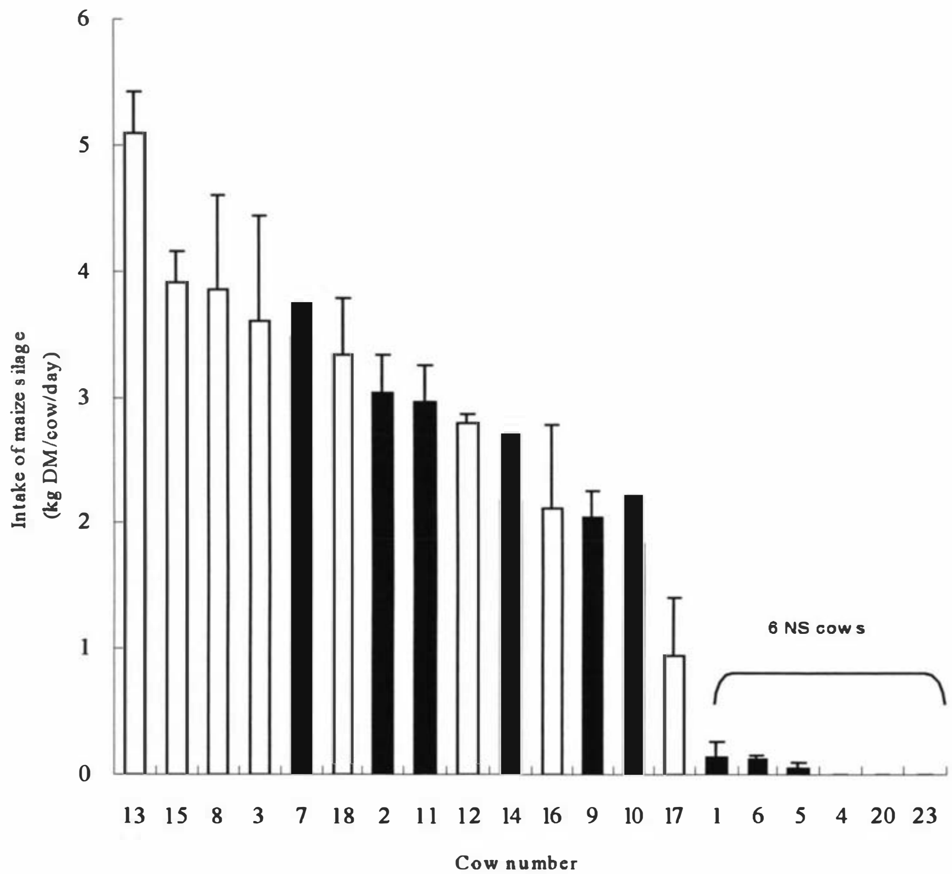
Table 2. Average daily DM intake of herbage and maize silage by individual cows. Treatment means are least square means (LSMEANS).

Daily Intake (kg DM per cow)	Treatment* S	Treatment* NS	SE**	P	Whole herd Mean ± SD
Herbage†	11.9	12.1	0.69	0.84	13.2 ± 0.49
Maize silage‡	2.6	0.0	0.18	< 0.01	3.8 ± 0.25
Total intake	14.5	12.1	0.60	0.04	17.0 ± 0.45

* S = supplemented, NS = not supplemented (n = 6).
** SE = standard error of LSMEANS (Degree of freedom of error term = 5).
† Whole herd mean calculated from the difference between herbage mass present before and after each grazing.
‡ Whole herd mean calculated from the difference between silage DM offered and refused.

Considerable variation (Figure 3) among individual cows was observed for the amount of maize silage DM eaten (Mean ± SD = 2.94 ± 1.06 kg; range = 5.09 – 0.94 kg; coefficient of variation = 36 %), although such variation was not significantly related ($P > 0.05$) to the amount of herbage eaten or to milk yield. Conversely, daily DM intake of herbage was positively related ($P < 0.01$) to milk yield (Figure 4). The S and NS cows spent similar amounts of time in grazing (9.0 and 9.5 h per day, respectively).

Fig. 3. The amounts of maize silage consumed by individual cows (average of two experimental periods). Black columns show the 6 paired cows. Bars are standard errors (n = 2).

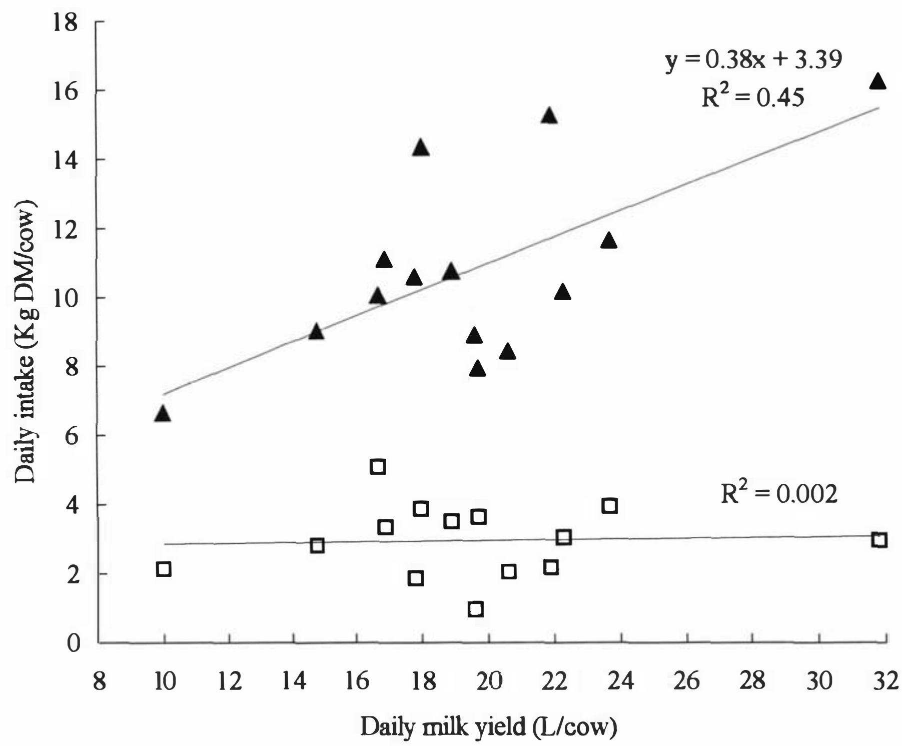


4. Discussion

The actual proportions of herbage and maize silage eaten were not successfully predicted by the non-negative least square (alkanes) method (method 1, Figure 1 *a*) of Dove and Moore (1995). This was expected because of the much lower concentrations of n-alkanes in maize silage than in herbage (Table 1). Using proportions instead of total quantities to overcome this problem did not improve the prediction, because the two forages contained very similar patterns of n-alkanes proportions. Nevertheless, the n-alkane technique has been used successfully by

Hameleers and Mayes (1998) to estimate individual intakes by dairy cows grazing perennial ryegrass pasture and supplemented with grass silage.

Fig. 4. Relationship between herbage (▲) and maize silage (□) intake and daily milk yield by individual dairy cows.



The present study showed that the Alkane & ^{13}C method can be used to estimate accurately the intake of herbage and maize silage by individual dairy cows (Figure 2). The ^{13}C method had been previously validated by Jones *et al.* (1979) using C_3 legumes and C_4 tropical grasses with cattle, sheep, goats and rabbits. The strong relationship found between the $\delta^{13}C$ in the faeces and the proportion of herbage in the diet (Figure 1 *b*) suggests that much of the variation observed between actual and predicted intakes (Figure 2 *a* and *c*) is likely to be a consequence of errors associated with the n-alkane technique rather than errors associated with the $\delta^{13}C$ method. Nevertheless, the present results suggest that precision in the estimations can be gained by averaging two independent estimates from successive collection periods for each individual animal (Figure 2 *b* and *d*). This reduction in the total error was expected because of the larger contribution of random variation, rather than mean bias or line bias, to the total MSPE.

The use of the $\delta^{13}C$ method has advantages and disadvantages. The main inconvenience is that the method does not allow different plant species within a photosynthetic pathway group (C_3 or C_4) to be distinguished. However, the contribution to the diet of different species in temperate pastures can be estimated by the n-alkanes technique, particularly to distinguish between perennial ryegrass and white clover (Dove and Mayes, 1996). Another disadvantage is that the digestibility coefficients of both forages (or group of forages) must be known. This could be avoided if one of the even-chained, dosed alkanes (usually C_{36}) is used to estimate total faecal output and the total diet digestibility is estimated by a naturally occurring odd-chained alkane (usually pentatriacontane, C_{35}). This approach, however, resulted in anomalous estimates of the total intakes in the present experiment (data not shown), probably because of the very low concentration of C_{35} in maize silage. Nevertheless, the determination of the *in vitro* OM digestibility of each feedstuff would still be required to correct the faecal ratios of $\delta^{13}C$ when both forage sources differ considerably in their digestible fractions (Jones *et al.* 1979). This constitutes a weakness of the technique, because of the inherent difficulties of sampling representative herbage by the "hand-plucking" method (Dove and Mayes, 1991).

A major potential advantage of the method is that neither stage of maturity of the plants (and so their nutritive value), nor the different proportions of species selected in the diet by individual cows, should affect the estimation of herbage:maize silage ratio. This is because the uptake of ^{13}C by the plant does not change significantly under a range of environmental conditions (Smith, 1972) and the $\delta^{13}C$ is very similar from the roots to the seeds.

The similar levels of herbage DM intake by the S and NS cows in Experiment 2 (Table 2) are in good agreement with the similar total time that the groups of cows spent grazing. The NS cows did not compensate for their lack of supplement by grazing for longer, probably because the NS cows preferred to wait for the rest of the herd to finish eating their MS before all returned to the pasture together. Consequently, the substitution rate was very low (< 0.1 kg herbage DM per kg maize silage DM), but similar to the substitution rate of 0.14 kg per kg observed by Stockdale (1996) when dairy cows grazing restricted pasture were supplemented with 4.4 kg DM of maize silage.

The averaged intake of maize silage for all the S experimental cows (n = 14) was lower than the mean value measured by weighing the silage offered and refused by the herd. This discrepancy could be due to real differences between the mean consumption of the whole herd (42 cows) and that of the sampled group of cows (14 cows), or to an underestimation of the individual intakes. The latter is less probable because the results of the validation trial (Experiment 1) showed no bias in the estimation of herbage and maize silage intakes. A third possible explanation is that silage intake could have been overestimated because some silage was inevitably dropped out of the bins by the cows, and the refusals inside the bins were collected and weighed only once at the end of each 5-day period. Curtis *et al.* (1994) also found a lower value (- 10 %) for the averaged intake than that expected from the difference between the supplement offered and refused, an effect attributed partially to losses during handling. In a similar way, the measurements of the herbage mass present before and after each grazing account for the total herbage DM "disappeared" rather than for the total herd intake (Chapter 5), which could explained the 9 % lower average value of herbage intake obtained with the alkane and $\delta^{13}C$ methods. Nevertheless, this comparison between methods should be taken cautiously, because it was precisely the weakness of techniques for estimation of herbage intake, such as the difference between herbage mass before and after grazing (Meijs *et al.* 1982), which have led to the search for alternative methods such as that described in the present paper.

Individual animals differed considerably in the amount of maize silage consumed daily from the troughs (Figure 3). Large differences in the level of supplement consumption between individual animals have been also reported for sheep (Curtis *et al.* 1994; Holst *et al.* 1994). The average intake of concentrate for a group of 50 grazing sheep was 559 g DM per head per day, but more than 30% of the animals ate less than 150 g DM/day while another 15% ate more than 1 kg DM per day (Curtis *et al.* 1994). Holst *et al.* (1994) also observed a large variation in supplement intake between grazing sheep when lupin seed was offered on the ground (coefficient of variation = 47 %) or from a feeder (coefficient of variation = 78 %).

The wide variation in the intake of maize silage between individual cows was unrelated to the level of milk yield (Figure 4). High-producing cows compensated for their higher requirements with a higher intake of herbage (Figure 4), resulting in greater total daily DM intake by these animals. Further research is required to investigate whether this compensatory increase in herbage intake can also take place with more restrictive herbage allowances than the 29 kg DM per cow offered in this study. The wide variations between cows in intakes of maize silage mean that calculations of the "average cow" nutritional requirements and responses will be inaccurate for those cows which eat less or more maize silage than others.

In conclusion, this study showed that the n-alkane and the $\delta^{13}C$ methods can be successfully combined to estimate the individual levels of DM intake of herbage and maize silage of grazing cows supplemented as a group. The validated methodology was applied in a commercial size dairy farm and considerable variation in supplement intake between individual cows was observed. Hypotheses regarding the use of maize silage as a supplementary feed for dairy cows grazing temperate pastures can now be tested under commercial farm conditions.

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Overview of Chapter 5

Systems research involves the application of common management guidelines in order to minimise the risk of introducing bias to the analysis. Due to the enormous number of interactions in the 'real-world' systems, however, such management guidelines may affect some of the key system-components differently. The investigation of the effects of the 'management' on some of these key-components of the system, in particular herbage growth and herbage intake, is one of the objectives of Chapter 5.

Further, the methodological approach regarding the combination of methods to estimate the DM intakes of herbage and maize silage by individual cows, which was the main topic of the previous chapter, is re-evaluated with an independent set of data in Chapter 5.

Chapter 5

Management of pasture-based dairy systems which differ in their calving season: effects on herbage accumulation, herbage DM intake, and total DM intake

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Abstract. The objectives of the present study were to investigate the effects of 3 dairy systems that differed in their calving season on 1) the herbage accumulation rates (HAR) and total herbage production, and 2) the DM intakes of herbage and maize silage by grazing cows and their relationship with milk yields. The 3 systems were managed according to a set of common guidelines during 3 consecutive years. HAR was estimated by the DM accumulated either on the ungrazed paddocks in successive weeks, or on grazed paddocks between 2 successive grazings ("pre/post-grazing herbage masses). Herbage DM intakes were estimated by the "pre/post" difference technique throughout the years, and also by the n-alkanes method at 3 different times of the year in one year. Overall, average HAR in each month were similar for all 3 systems and for the 2 methods. However, small seasonal differences in HAR between calving systems were observed in spring and summer, which were related to the previous pasture management (i.e. silage vs. non-silage paddocks). Herbage DM intakes varied seasonally ($P < 0.05$) but independently of the calving system ($P > 0.05$). Compared to intakes calculated from energy requirements, the "difference" method overestimated intakes by (mean ± s.d.) 10 ± 23%, while the n-alkanes method (early and late spring), or the "n-alkanes & ^{13}C method" (autumn), underestimated intakes by 7 ± 7%. Cows from different calving systems offered 8.9 kg or 2.5 kg maize silage DM per cow daily in the paddocks consumed an average of 6.0 and 1.4 kg, respectively, and a large variation was observed among individual cows (ranges 2 to 10 kg and 0.2 to 2.9 kg, respectively). The discrepancy between the quantities of silage DM offered and the measured intakes was attributed mainly to silage wastage, though a slight underestimation by the method is possible. In conclusion, applying the same grazing management decisions to systems with contrasting calving dates resulted in only small seasonal differences in pasture HAR, which disappeared when all data were combined. Because of the management rules used for all systems, intakes of grazed pasture were seldom affected by calving season but were related to pasture accumulation rate, and more realistic estimates of intake were obtained with the n-alkanes method than with the pre/post method. When maize silage is fed in the paddocks, large wastage and large variation in intakes between individual cows can be expected.

Keywords: herbage accumulation rate; dry matter intake; calving date; dairy

1. Introduction

Autumn calving systems are feasible alternatives to the traditional, spring-calving dairy systems in New Zealand (García and Holmes, 1999, Chapter 1). However, contrasting calving seasons also imply different relationships between feed requirements and herbage availability through the year. Thus, deficits of pasture availability for the spring-calved cows occur normally during late lactation when requirements (and total intakes) are also decreasing, but they occur at the peak of lactation (winter) for autumn-calved cows. The effects of these different requirements in contrasting systems on pasture herbage accumulation pattern and total pasture production is not known, and the relationships between herbage DM intakes and time of the year between contrasting calving systems have not been researched.

The amount of dry matter (DM) consumed daily by a dairy cow constitutes the single most important factor determining its performance in any production system. In dairy systems in which the cows are housed and fed a mixture of conserved forage and concentrate feeds, daily DM intakes can be measured with relative simplicity. In pasture-based systems, however, intakes cannot be "measured" but can only be "estimated" by different methods, thus an exact knowledge of the amount of DM eaten by grazing animals is not possible. Further, in these systems, DM intakes are affected by a number of herbage-related factors such as herbage mass (HM) and quality, herbage allowance, grazing area, and supplement intake, factors that can differ between seasons of the year (SCA, 1990). In addition, intakes are also affected by animal-related factors such as the cows' liveweight and milk yield, and these pasture- and animal-factors interact with each other, which complicates the situation further. In New Zealand, where about 95% of the dairy cows calve in late winter-early spring, seasonal and physiological factors are usually confounded, and little is known about the possible interactions among the above factors when cows calve in the autumn rather than in the spring.

In studies of whole farm pasture-based systems, herbage DM intake can be estimated by measuring the amount of herbage present immediately before and after each grazing (the "difference method", Frame, 1993). An advantage of this method is that the same information can be combined with future estimates of HM on each paddock, to enable calculation of the amount of herbage DM accumulated between 2 successive grazings and thus, the linear accumulation rate. However, the use of the difference method with a herd of cows can estimate only the average intake for the group, and not the intakes of individual cows. In addition, its accuracy in whole-system studies remains to be established.

An alternative to the difference method is the estimation of herbage DM intake by individual animals using external markers, such as the n-alkanes (Dove and Mayes, 1991). Although a strict validation of any method with grazing animals is not possible, the n-alkanes method has been validated with animals fed fresh herbage indoors both overseas (see reviews by Dove and Mayes, 1991, 1996) and in New Zealand (García *et al.* 2000a, Chapter 4), and has been widely used with grazing dairy cows (Reeves *et al.* 1996; Robaina *et al.* 1997; Buckley *et al.* 2000). Because estimates of intakes by individual cows can be obtained with minimal disturbance of the actual farming conditions, the method provides a useful tool for understanding 'real-world' farming systems (García *et al.* 2000a, Chapter 4). However, the method is relatively expensive and provides estimates which are based on relatively short periods of time (usually 1 or 2 weeks).

An additional problem with any of the previous methods becomes apparent when grazing cows are supplemented with conserved forages such as pasture or maize silage. A better knowledge of individual intakes of herbage and silage under different situations and their relationship with milk yields is crucial for a more complete understanding of these pasture-based dairy systems. However, the n-alkanes method can still be used, either alone to differentiate between herbage and silage intakes in cows being supplemented with pasture silage (Hameleers and Mayes 1998), or in combination with ^{13}C determinations if the supplement is maize silage (García *et al.* 2000a, Chapter 4). Although the latter authors have validated the methodology, the combination of methods has not yet been tested with an additional set of independent data.

A 3-year system study was conducted at Massey University from 1996 to 1999 to compare contrasting calving systems, and physical results as well as detailed studies of the cows' lactation curves have been published elsewhere (García *et al.* 2000b [Chapter 2] and García and Holmes 2000 [Chapter 3], respectively). The present paper focuses on the effects of these contrasting calving systems on 1) herbage accumulation and total herbage production (estimated using 2 different methods), and 2) total DM intakes by the cows and the relationship between intakes and milk yields by individual cows. Within the system study, the n-alkanes method was utilised on approximately 40 autumn- and 40 spring-calved cows at 3 times of the year (early spring, late spring, and autumn) to investigate the effects of time of the year and season of calving on DM intake, and, where possible, to evaluate the performance of this method in comparison to the difference method. The third objective of this study was to investigate the variation in DM intakes of maize silage by individual grazing cows (fed as a group), while re-evaluating at the same time the performance of the "n-alkanes & 13C method" which has been proposed for that aim (García *et al.* 2000a, Chapter 4).

2. Materials and Methods

2.1. Overview of the system study

The system study was a 3-year experiment in which the physical and economical performances of 3 calving systems of 40 ha each (100% of cows calving in the autumn [100A], 100% in the spring [100S], and 50% in the autumn-50% in the spring [50/50]) were compared. The individual herds within the latter system are referred to as 50A and 50S, respectively. The numbers of cows in the 3 systems were approximately 80, 100 and 90, respectively. More details about the experiment layout and procedures are given elsewhere (García *et al.* 1998, 2000b [Chapter 2]).

2.2. Grazing management and pasture measurements

Grazing management was based on a common set of decision rules for all systems during the 3 years. They included the maintenance of the average whole-system HM at around 2000 kg DM/ha, post-grazing residual HM for lactating cows no less than 1600 kg DM/ha and pre-grazing HM of at least 2600 kg DM/ha. Grazing management decisions were made weekly using the above guidelines and the measured values for the previous week, together with the results of a simple balance between the herds' requirements and the herbage accumulation rate (HAR) predicted for the following week. Forage harvested from each system (conserved as either silage or haylage) and maize silage (harvested on farm in Year 1 and purchased in the Years 2 and 3), were fed to the cows whenever a potential deficit in herbage intake was apparent from the weekly measurements and the decision rules.

Pasture measurements were carried out on individual paddocks (average size = 2 ha), utilising a rising-plate meter (Michell 1982). The HM of each paddock was measured 1) once a week on all paddocks by taking approximately 30 plate-meter readings per paddock (all 3 years), and 2) immediately before and after each grazing on each grazed paddock (the "difference method") by taking at least 100 plate-meter readings (November to June in Year 1 and throughout Years 2 and 3). The latter was observed to be the minimum number or readings required in order to minimise the standard error of the estimated mean value (Appendix), although its application to the weekly measurements was impractical.

The average whole-system HM was estimated each week, and the amount of DM that had accumulated on each ungrazed-paddock during the previous week was calculated from the successive weekly measurements of HM on all paddocks. The daily DM intake of each herd (one averaged value per herd), and the amount of DM accumulated on each paddock between 2 consecutive grazings, were estimated from the measurements of pre- and post-grazing HM on every paddock.

2.3. Estimation of whole herd DM intakes (difference method)

Daily herbage DM intake was calculated as the difference between total pre- and post-grazing HM on each grazed paddock, divided by the number of grazing cows and the number of days spent on each paddock. Other variables of interest derived from these data were daily herbage allowance (kg DM/cow), total daily area (m^2) grazed per herd and per cow, and the ratio between total grazing area and area grazed per 24 h (instantaneous rotation length, days). The final data set consisted of over 1600 individual paddock records.

The plate meter was calibrated by cutting 54 × 0.2 m^2 quadrats to ground level in September, October, November, and December of Year 2 only. A standard equation (HM= 200 + 158 × Plate Meter Reading) was used for the rest of the year and the same combination of equations (i.e. Year 2 calibrations from September to December and the standard equation for the rest of the year) was used for Year 3. This was done as season rather than year is the main source of variation in the equation parameters (Bishop-Hurley, 1999). In addition, resources in the present study were concentrated primarily on the relative comparison between systems rather than on the absolute values of measurements.

Herbage DM intakes estimated by the above equations were also compared with intakes calculated from values of HM estimated from the seasonal equations of Hainsworth (1999) and with the dynamic calibration equation developed by Bishop-Hurley (1999). The latter equation was developed from data collected during 3 years from Massey University's No 4 Dairy Farm, which is situated within 5 km of the farm used in the present study. The seasonal equations (Hainsworth 1999) were derived from the main dairy areas in New Zealand and several years of measurements.

2.4. Measurement of individual DM intakes (n-alkanes method)

Intakes of herbage DM by individual cows were measured at 3 different times in the last 12-months of the systems comparison: Period 1) August-September 1998, Period 2) November-December 1998, and Period 3) May-June 1999, which corresponded to mid, late and early lactation for the autumn-calved cows and to early (Period 1) and mid (Period 2) lactation for the spring-calved cows, respectively. Spring-calved cows were not included in Period 3 (late lactation) because these cows had been dried-off earlier than planned due to a severe drought in late summer-early autumn, 1999.

Approximately 20 cows were selected from each of the four herds prior to Period 1. The selected groups of cows were balanced in terms of days in milk at the start of the experimental period, previous milk yields, age, and breeding worth. The same cows were reused in the 3 experimental periods, although some had to be culled before the third period and were replaced. All the experimental cows were identified by coloured collars and were managed with their respective herds at all times.

On day 1 of each of the 3 experimental periods, each cow was dosed with a controlled release device capsule containing 8 g of dotriacontane (C_{32}) and 8 g of hexatriacontane (C_{36}) (Captec™, New Zealand) with a constant release rate for each n-alkane of approximately 400 mg per day. Faecal samples were collected once daily (approximately between 0800 h and 1000 h) from each individual cow in the paddocks during two 5-day periods (days 7 to 12 and 15 to 20). Cows in each herd were observed closely by 3 or 4 people (in 2-ha paddocks), and faecal samples were taken from the ground immediately after defecation and with special care to avoid soil contamination. All samples were frozen within 3 h after collection, and were later freeze-dried. A composite sample was created, for each cow within each 5-day period, by adding equal amounts of faecal dry matter from each of the 5 sampling days. Thus, 2 composite samples were prepared and analysed for each individual cow, resulting in a total of 406 individual estimates of DM intake for subsequent analyses.

Herbage samples, hand-plucked to simulate the pasture grazed by the cows, were taken from each paddock grazed during the two 5-day periods (Cosgrove *et al.* 1998), and the nutritive value was determined for each individual sample by NIRS analysis (Corson *et al.* 1999). Herbage and faecal samples (all 3 periods), and maize silage samples (period 3) were analysed for concentrations of n-alkanes by gas chromatography (Model 5890 A, Hewlett Packard, Avondale, P.A.) and for concentrations of the stable isotope ^{13}C by mass spectrometry (Europa Scientific Tracermass).

2.5. Calculations and Statistical Analyses

Measurements for the difference method were made at the beginning (post-grazing HM) and at the end (pre-grazing HM) of the regrowth period for each paddock. Therefore, an implicit assumption of this method is that DM accumulates at a linear rate during such periods. In this study, daily HAR estimated by the difference method for each individual paddock were combined into one averaged value per month, and these means were then analysed as repeated measures using restricted maximum likelihood (REML) procedures available in Proc Mixed (SAS 1997). This method allows the covariance structure of the data to be modelled and is therefore more suitable for autocorrelated data (Littell *et al.* 1998).

Grazing residuals (post-grazing HM) were classified into 7 categories defined arbitrarily at intervals of 200 kg DM/ha (< 1300 kg, 1300-1500,…,> 2300 kg). These categories were used to investigate the effects of residual HM on the HAR during the subsequent regrowth period, using generalised linear models (SAS 1997).

The relationships between herbage-related variables (pre- and post-grazing yields of HM, herbage allowance, grazing area, grazing duration) and herbage DM intake estimated by the difference method were investigated by multiple regression analyses using stepwise procedures in SAS (1997).

Data for individual intakes estimated using the n-alkanes method (Periods 1 and 2) and the "n-alkanes & ^{13}C method" (Period 3) were analysed by REML procedures (SAS 1997). Fixed effects included system (calving date), period, and the interaction between the 2 whilst the individual cows (nested within system) were used as random effect. In addition, for cows that lost liveweight around each period of measurements (cows were weighed and condition scored monthly during the 3 years), daily intakes were adjusted by the amount of energy theoretically made available to the cow due to tissue mobilisation, assuming 32 MJ ME/kg liveweight lost (Holmes *et al.* 1987). Energy-based predicted values of individual DM intakes were calculated assuming 0.6 MJ ME/kg liveweight$^{0.75}$ required for maintenance, 38.5 MJ ME/kg tissue gain or 32 MJ ME/kg tissue lost, and 4.8 MJ ME required per litre of milk (Holmes *et al.* 1987). The relative mean prediction error (RMPE), which is the mean error of prediction expressed as a percentage of the average "measured" intake, was used to compare measured (estimated by the n-alkanes method) and predicted (energy-based relationships) values (Bibby and Toutenburg 1977). For all analyses, significance was declared at $P < 0.05$ unless otherwise stated.

3. Results

3.1. Herbage accumulation rate and pasture production

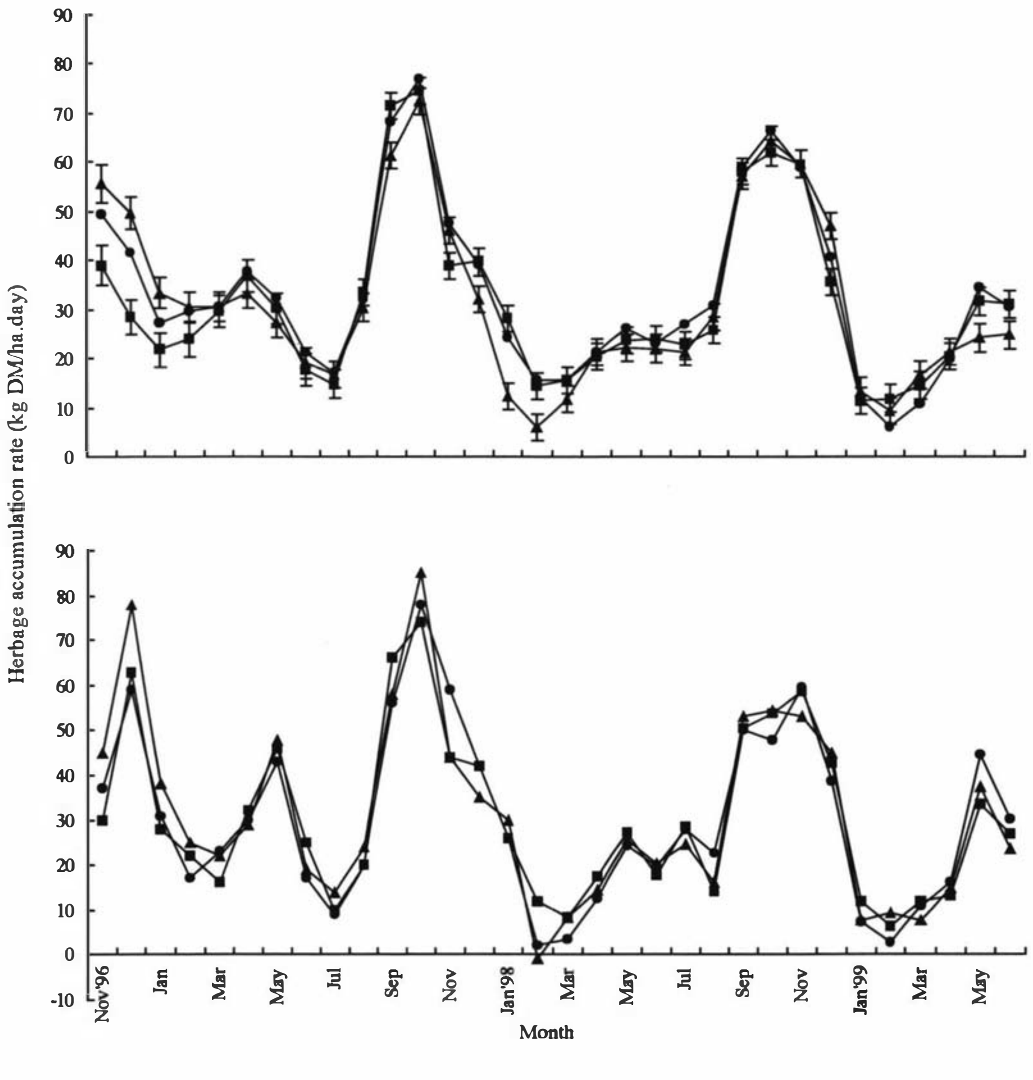
Overall, the first year of the trial was characterised by "average" values for soil temperature and total rainfall. In contrast, Years 2 and 3 were warmer and drier than the 15-year averages for the farm (Table 1). These differences were more marked during the summer periods (December to March), when soil temperature was 0.6 and 1.8 °C higher and total rainfall was 77 and 180 mm lower (for Years 2 and 3, respectively) than the average year (Table 1).

Table 1. Mean soil temperature (10 cm) and total rainfall during 12-month periods (July-June) and 4-month summer periods (December-March) for the 15-year average and for each Year of the system study.

	12-month period (Jul-Jun)			
	15-year average	1996-97 (Year 1)	1997-98 (Year 2)	1998-99 (Year 3)
Mean soil Temperature at 10 cm (°C)				
Whole 12-month period	12.7	13.0	13.2	13.9
December to March	17.5	16.9	18.1	19.3
Total rainfall (mm)				
Whole 12-month period	995	990	855	958
December to March	309	285	232	129

The rate of herbage accumulation followed a strong seasonal pattern in all years and for all systems, with similar results observed using either the pre/post grazing data (Fig. 1a) or the weekly data for each paddock (Fig. 1b). In all the three years, the spring-early summer period (September-December; 33% of the year) contributed between 50 to 60% of the total annual herbage production (data from the whole period in which both weekly- and pre/post-based measurements were available are shown in Fig. 1).

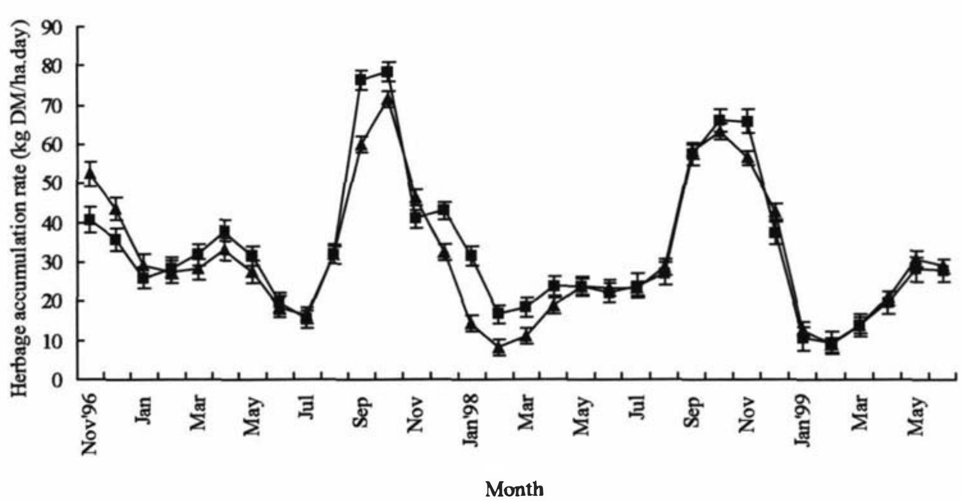
Fig. 1. Herbage accumulation rates for the 100A (■), 100S (▲), and 50/50 (●) systems from November 1996 to July 1999. Values are the monthly averages obtained by the "difference" (a) and the "weekly" (b) method. Vertical bars are s.e. of the least square means.



Average HAR was higher for the 100S than for the 100A system during the first summer of the trial, but the opposite effect was observed during the spring and summer of Year 2 (Fig. 1a). These effects resulted in significant differences in the estimated annual HAR between these 2 systems in Year 2. However, when all the combined data were analysed using either repeated measurements models or years as replicates, total annual pasture production was similar between systems, averaging 11.8 ± 0.5 t DM/ha/year with either of the 2 methods utilised. The coefficient of correlation between the monthly values calculated by the 2 methods from November 1996 to June 1999 was 0.9.

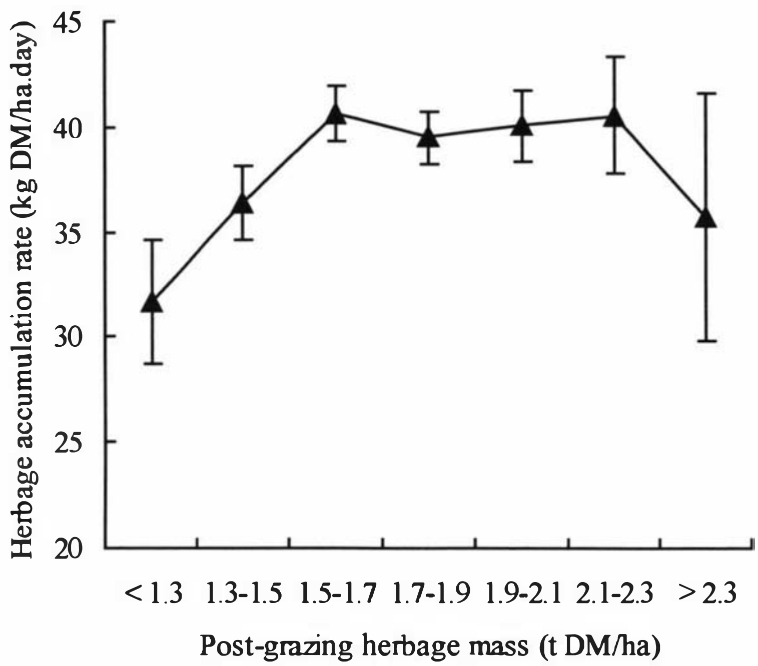
Paddocks that were closed for silage at least once during Year 2 had a significantly higher HAR during the closure period than the non-silage paddocks during the same period (Fig. 2). Herbage in the silage paddocks accumulated at a slower rate immediately after the silage had been harvested, but at a significantly higher rate thereafter until both groups of paddocks achieved similar HAR again in the following autumn. All these effects were observed in each of the 3 calving systems (data not shown), although they were more marked for the 100A system than for the other 2 systems. Similar effects were observed during the spring of Year 3, in which the herbage in the silage-paddocks (average of all systems) accumulated at a higher rate than the herbage in the non-silage paddocks (Fig. 2). However, in Year 3 the effects was less consistent when analysed for each individual system and both groups of paddocks had similar HAR from early summer up to the end of the experiment in the following winter (June 1999).

Fig. 2. Herbage accumulation rates for pastures (i.e. paddocks) that were conserved as silage at least once during each 12-month period (July-June) (■), or were grazed (▲) throughout the same periods. Vertical bars are s.e. of the least square means.



In the 2 years and for all seasons, the rate of herbage accumulation was about 20% lower ($P < 0.05$) when the residual HM left after each grazing was less than 1300 kg DM/ha (Fig. 3) compared with residual HM greater than 1500 kg DM/ha. Average HAR following grazing (about 40 kg DM/ha/day on average for the whole year), was not affected by residuals between 1500 and 2300 kg DM/ha, whilst HAR was slower following residuals greater than 2300 kg DM/ha. These effects did not change ($P < 0.05$) after including the pre-grazing-HM of the following grazing as a covariate in the model to account for possible differences in the pre-grazing HM when re-growing from different residual levels.

Fig. 3. Relationship between post-grazing herbage mass and the daily rates of herbage accumulation. Vertical bars are s.e. of the least square means.



3.2. DM intake

Herbage DM intake, as estimated by the difference technique, followed a strong seasonal pattern in both Years 2 and 3 (Fig. 4). However, herbage intakes in any one season were similar for autumn- and spring-calved cows. Intakes were highest in September and October in both years and lowest in February, January, and August in Year 2, and from February to March in Year 3. Standard errors of the monthly adjusted means were relatively large for both systems, particularly for May and July 1999 for the spring-calved cows. Compared to the calibrations derived from the present study, values for herbage DM intake from the other calibration equations were either much greater in the summer-autumn period (Bishop-Hurley 1999), or much smaller during the spring period (Hainsworth 1999) (Fig. 5).

Fig. 4. Monthly average herbage DM intakes by 100A (■), and 100S (▲) cows for Year 2 (a) and Year 3 (b). Vertical bars are s.e. of the least square means.

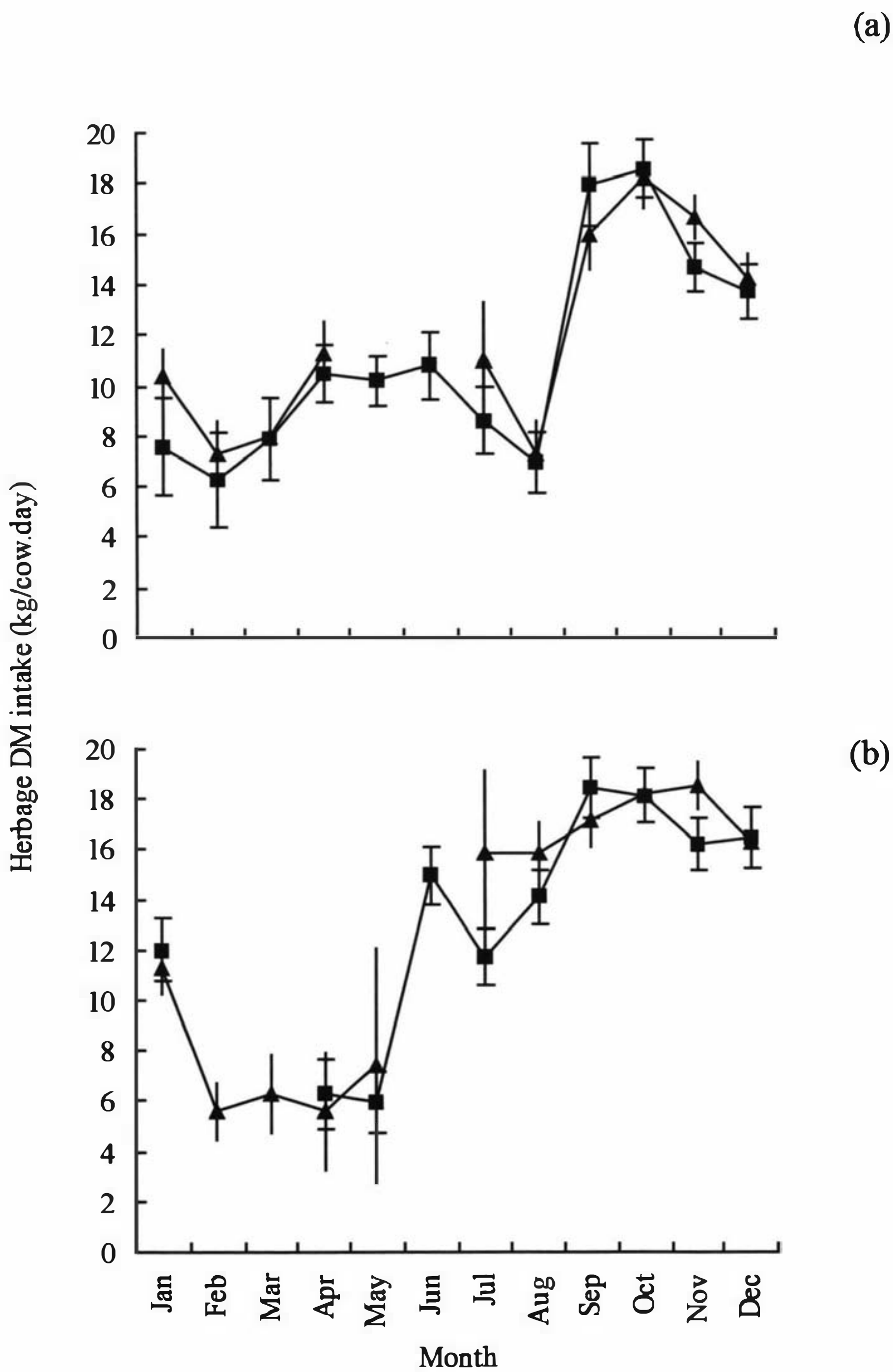
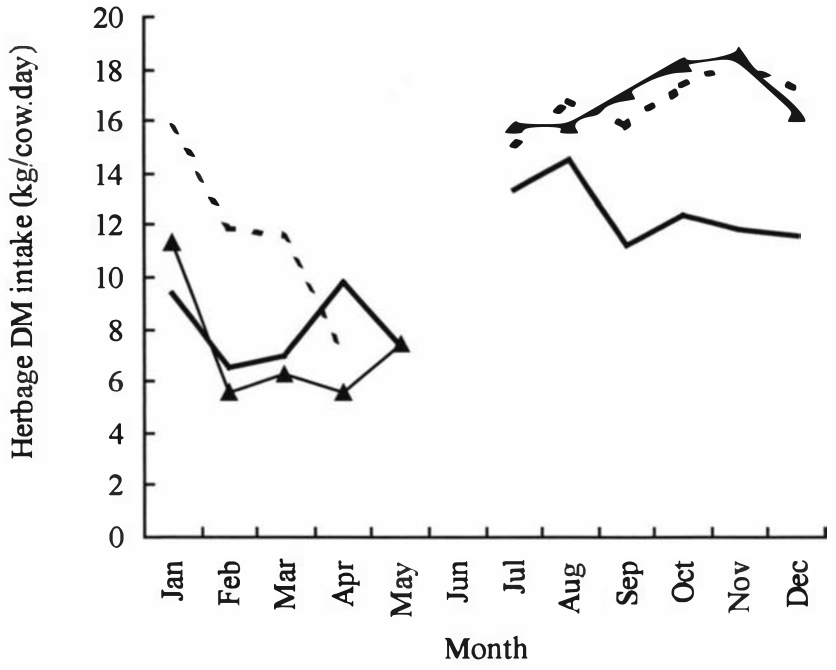


Fig. 5. Monthly average herbage DM intakes by 100S cows in Year 3 estimated using the plate meter calibration equations derived from the present study (▲), the dynamic calibration equation developed by Bishop-Hurley (1999) (broken line), or the seasonal equations developed by Hainsworth (1999) (solid line).



Total herbage DM intake estimated by the difference method was positively and statistically correlated with pre- and post-grazing HM and herbage allowance, and negatively correlated with the number of days spent by the cows on each paddock. On average for all data, herbage DM intake increased by 0.2 kg per kg DM of increase in the daily herbage allowance. Including these variables in multiple regression analyses resulted in models that accounted for about 85% of total observed variation for all seasons and years, although including their quadratic terms as additional independent variables increased R^2 to over 90% (Table 2).

Table 2. Multiple regression models and coefficients of determination for herbage DM intake (kg DM/cow.day).

	Regression model[A]	R^2
Linear	$2.6_{(0.3)} + 0.009$ PreG HM $_{(0.0001)} - 0.012$ PosG HM $_{(0.0001)} - 0.99$ GD $_{(0.06)} + 0.2$ A $_{(0.004)}$	0.85
Quadratic	$-8.5_{(0.9)} + 0.012$ PreG HM $_{(0.0006)} - 0.0000005$ PreG HM^2 $_{(0.0000001)} -$ 0.01 PosG HM $_{(0.0002)} + 0.44$ A $_{(0.009)} - 0.002$ A^2 $_{(0.00007)} - 0.05$ GD^2 $_{(0.004)}$	0.90

[A]PreG HM = pre-grazing herbage mass (kg DM/ha); PosG HM post-grazing herbage mass (kg DM/ha); GD = grazing duration (days); A = herbage allowance (kg DM/cow.day). Values in parenthesis are s.e. of the parameter estimates.

Table 3. Herbage mass before and after grazing, grazing management, and average daily DM intake for each system at the 3 times of the year when intakes by individual cows were measured.

		Herbage Mass						Average daily intake of DM: "Pre/post" Difference method			Average daily intake of DM: n-alkane method[1]		
Period	Farm	Before grazing	After grazing	Cows	Area grazed	Instantaneous Rotation length	Daily Herbage Allowance	Herbage	Maize Silage	Total	Herbage	Maize Silage	Total
		(kg DM/ha)		(N°)	(ha/ day)	(days)	(kg DM /cow)	(kg DM/cow)			(kg DM/cow)		
1:	100A	2578	1806	80	1.8	22	58.1	17.3	0	17.3	15.4	0	15.3
Sep	100S	2579	1687	100	1.9	21	49.7	17.2	0	17.2	14.6	0	14.6
1998	50/50	2899	1758	98	1.9	23	55.9	21.8	0	21.8	15.2	0	15.2
2:	100A	3015	1972	78	1.3	31	48.8	16.3	0	16.3	15.0	0	15.0
Dec	100S	2990	1967	99	1.4	29	42.3	14.6	0	14.6	15.2	0	15.2
1998	50/50	2838	1968	95	1.5	29	44.2	13.5	0	13.5	15.6	0	15.6
3:	100A	2333	1580	81	0.9	46	25.1	7.9	8.9	16.8	7.1	6.0	13.1
May	50A	3135	1805	46	0.5	NE[2]	36	14.6	2.5	17.1	10.3	1.4	11.8
1999[2]													

[1] n-alkanes method in periods 1 and 2; *n-alkanes &* ^{13}C method in period 3.
[2] All the spring-calved cows had been dried-off prior to Period 3 due to a severe drought.

There were no significant differences between the 3 systems in pre- and post-grazing HM, area grazed daily, rotation length, DM allowance, and days spent grazing a paddock, but significant differences were observed between seasons. This is shown for 3 different times of the year in Table 3, which summarises the herbage characteristics and grazing management during the 3 periods of individual-intake measurements. The chemical composition of the herbage grazed in each of these 3 periods is shown in Table 4. Neither the effects of system nor the interaction system × time of year were significant, thus results are presented as the averages for each period (time of year). For all the analysed variables, there were significant differences ($P < 0.05$) between September (Period 1) and December (Period 2), although concentrations of crude protein, total lipids, ash, acid detergent fibre, and neutral detergent fibre in May-June (Period 3), were similar to those of early spring (Period 1). Overall, herbage was of very high nutritive value in early spring and autumn. However, the herbage organic matter was 5% and 12% more digestible in early spring than in autumn and late spring, respectively.

In agreement with the general patterns of herbage intake estimated by the difference method, total herbage intakes measured by the n-alkanes method differed ($P < 0.001$) between seasons and, within the spring, intakes did not differ between

Table 4. Average chemical composition of herbage at three different times (intake evaluation periods).

Period[2]	Chemical composition[1]								
	CP	Lipids	Ash	ADF	NDF	CHO	DCAD	OMD	ME
	% of DM						mEq/kg DM	% of OM	MJ/kg DM
1 (Sep'98)	26.3a	3.7a	11.8a	21.5b	36.4b	8.7a	380a	85.0a	11.7a
2 (Dec'98)	17.9b	3.1b	10.5b	26.7a	43.9a	9.3a	307b	76.0c	10.6c
3 (May'99)	28.5a	3.7a	11.5a	20.9b	35.5b	7.4b	206c	81.1b	11.0b
s.e.	0.83	0.11	0.19	0.53	0.68	0.48	16.7	0.99	0.13

[1]CP=crude protein; ADF= acid detergent fibre; NDF= neutral detergent fibre; CHO= soluble carbohydrate; DCAD = dietary cation-anion difference; OMD= organic matter digestibility; ME= metabolisable energy
[2]Values within a column with different letters differ statistically ($P < 0.05$)

the 3 systems despite the fact that the cows in different systems were at different stages of lactation (Table 5). However, herbage (and total) DM intakes were much lower ($P < 0.01$) during the following autumn when all the autumn-calving cows had recently begun a new lactation and only limited pasture was available and offered, particularly for the 100A system. In contrast with the difference method, for which DM intake peaked in September-October and decreased subsequently, intakes estimated by the n-alkanes method differed only slightly between early spring (September, 15.0 kg/cow) and late spring (December, 15.4 kg/cow), and were lower in early spring than those estimated by the difference method. For total DM intake (i.e. herbage only for all cows during Periods 1 and 2, and herbage plus maize silage for the autumn-calved cows in Period 3), neither the system effect nor the interaction between system and time of the year were significant (Table 5).

Table 5. Average daily intakes by individual cows of herbage (n-alkanes method for Periods 1 and 2) and herbage and maize silage (n-alkanes & ^{13}C method for Period 3) and feed conversion efficiencies for each system (or each herd for the 50/50 system) at the 3 times of the year when intakes by individual cows were measured.

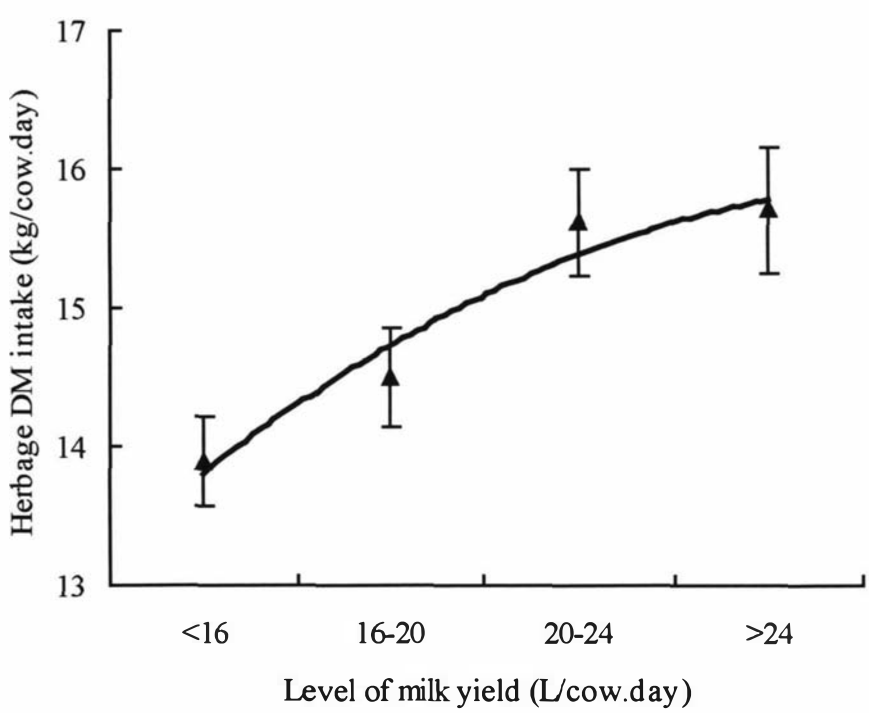
	System (herds)[1]												Statistical effects[4]		
	100A			100S		50A			50S		n[2]	s.e.[3]	S	T	S × T
Period	3	1	2	1	2	3	1	2	1	2					
SOL[5]	Early	Mid	Late	Early	Mid	Early	Mid	Late	Early	Mid					
Time	May	Sep	Dec	Sep	Dec	May	Sep	Dec	Sep	Dec					
DM Intake[6]															
Pasture	7.1	15.4	15.0	14.6	15.2	10.3	14.9	15.1	15.4	16.2	196	0.55	0.12	<0.001	<0.001
Maize Silage	6.0	0	0	0	0	1.4	0	0	0	0	202	0.14	<0.001	<0.001	<0.001
Total	13.1	15.4	15.0	14.6	15.2	11.8	14.9	15.1	15.4	16.2	196	0.58	0.36	<0.001	0.37
Total[7] (LW)	14.8	15.5	14.7	15.6	16.2	13.3	15.7	16.4	15.4	15.3	158	0.76	0.9	0.006	0.06
Predicted[8]	14.5	14.3	17.2	15.2	16.4	12.6	15.3	18.8	16.0	18.8	162	0.94	0.29	<0.001	0.18
FCE[9]	115a	105a	75b	127a	82b	117a	89b	82b	110a	86b	185	5.7	0.006	<0.001	0.004

[1]No estimates were made on spring-calved cows in late lactation (May) because these cows were dried-off earlier than planned due to a severe drought
[2]Number of observations (each observation is the mean of 2 separate intake estimates). *n* changes among variables as a result of performing operations on missing values
[3]The largest standard error of all LSMEANS for each variable is presented here
[4]S = system (or herds in the case of the 50/50 system), T = time of the year
[5]SOL = stage of lactation
[6]Kg/cow daily
[7]Total DM intake corrected by the amount of energy supply by tissue mobilisation [assuming 32 MJ ME/kg tissue lost.

L Footnotes 8, 9 ?

Overall, average DM intakes calculated from the measured values for liveweight, liveweight change, and milk yield together with theoretical energy requirements, were in closer agreement with the average of total DM intakes estimated by the n-alkanes method (RMPE = 10.7%), than with the group-based averages estimated by the difference method (RMPE = 23 %). However, the correlation coefficient between pairs of calculated (from energy requirements) and "measured" (n-alkanes method) values was only 0.48 ($P < 0.001$) and the RMPE was relatively high (24 %).

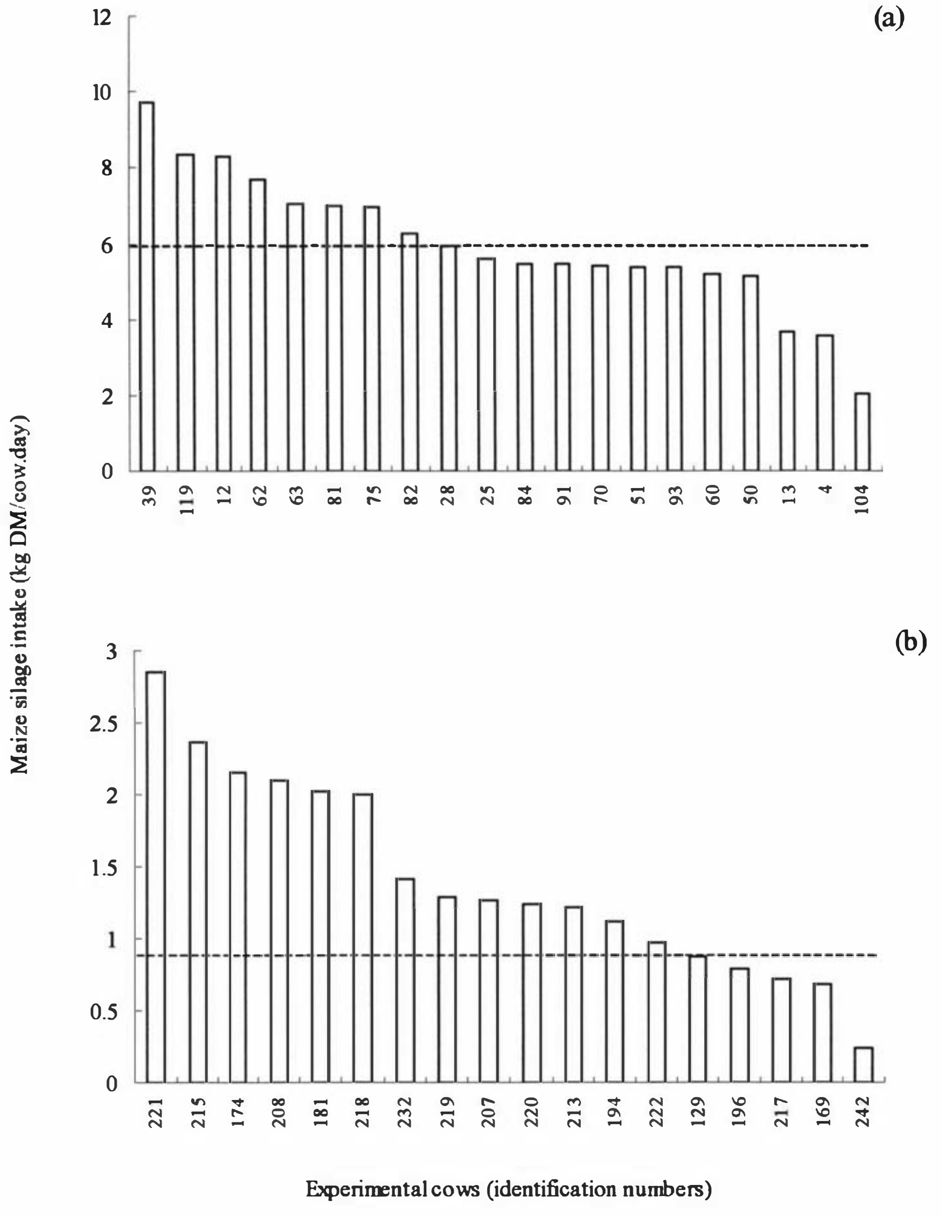
Fig. 6. Relationship between the level of milk yield (L/cow.day) and the total average DM intakes (n-alkanes method) by individual cows (kg/cow.day) in the three combined periods. Vertical bars are s.e. of the least square means, n = 202.



3.3. DM intake by individual cows and efficiency of milk production

The efficiency of feed conversion (g milkfat + milk protein/ kg total DM intake measured by the n-alkanes method) was greatest for cows in early lactation regardless of the calving season (range 110-127 g/kg). However, for cows in mid lactation, autumn-calved cows (early spring) had higher conversion efficiencies than spring-calved cows (late spring), which resulted in a significant ($P < 0.01$) interaction between calving season and time of the year. This effect was more marked for the 100A cows than for the 50A cows (Table 5).

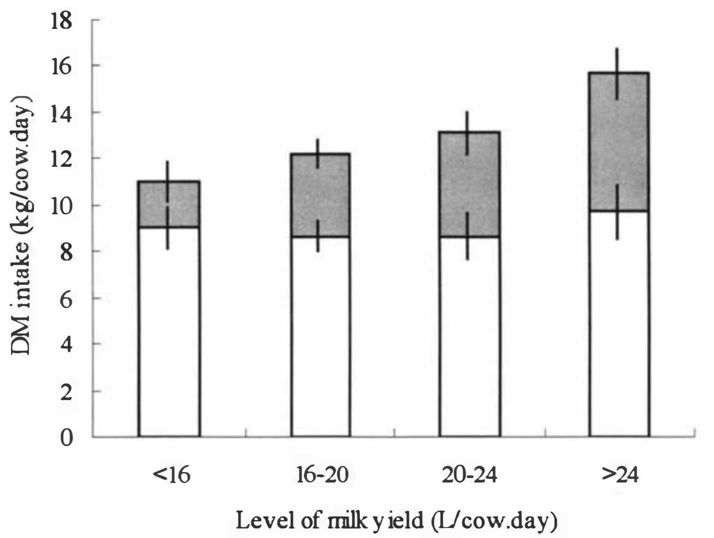
Fig. 7. The amounts of maize silage (average of 2 experimental periods) consumed by individual 100A (a) and 50A (b) cows. Broken lines show the average amounts consumed by each group of cows.



High producing cows had greater ($P < 0.05$) daily DM intakes (measured by the n-alkanes method) than low producing cows, an effect that persisted after adjusting the DM intakes to account for liveweight losses. This effect was observed not only for the combined data (the 3 seasons together, Fig. 6) but also for each individual season, although in the latter case the effect was significant for late spring and autumn but not for early spring (data not shown). Despite these general effects, however, the correlation coefficient between pairs of individual DM intakes (from the n-alkanes method) and their corresponding milk yields was only 0.23 ($P < 0.01$). Adjustment of total DM intakes by the amount of energy released from tissue mobilisation improved the relationship between the 2 variables slightly ($r = 0.36$, $P < 0.01$).

In Period 3 (May-June), when the cows were supplemented with maize silage, the average values of maize silage DM intakes estimated by the "n-alkanes & ^{13}C method" (6.0 and 1.4 kg DM/cow/day for 100A and 50A cows, respectively) were smaller than the average amount of silage DM actually offered to each herd during the same period (8.9 and 2.5 kg DM/cow/day, respectively).

Fig. 8. Relationship between the level of milk yield (L/cow.day) and the average DM intakes of herbage (open columns) and maize silage (solid columns) by individual cows (kg/cow.day) in Period 3 (May-June). Vertical bars are s.e. of the least square means, n = 38.



The intakes of silage DM varied markedly among individual cows, ranging for the 100A cows between 2.0 and 10.0 kg /cow daily (coefficient of variation = 30%, Fig. 7a), and for the 50A cows between 0.2 and 2.9 kg (coefficient of variation = 49%, Fig. 7b). This variation was positively associated ($P < 0.05$) with increasing levels of milk yield (Fig. 8). Conversely, herbage DM intakes were similar for cows across all production level categories.

4. Discussion

4.1. Herbage accumulation rate and total herbage production

One objective of this study was to investigate the effects of contrasting calving date systems on the HAR and total herbage production using 2 different methods.

Herbage measurements included estimates of HM on every paddock both at weekly intervals and immediately before and after each grazing, and HAR calculated by any of these methods were very similar (Fig. 1).

An advantage of the 'weekly' method is that each pasture (i.e. paddock) has 52 "points" of HM estimates per year, and consequently, accumulation rates are assumed to be linear only during each 7-day period. This contrasts with the much smaller number of HM estimates (usually between 8-14 per year) by the "difference method", in which accumulation rates for each paddock are assumed to be linear during the whole regrowth period regardless of its length. A second advantage of the "weekly" method is that the average HM of the whole farm can be calculated for each week. However, pre- and post- HM were estimated with a minimum of 100 plate meter readings distributed across the whole paddock, while the number of readings was necessarily smaller (25-30) for the "weekly" method in which the whole farm (120 ha) was measured on 1 occasion by "crossing" all its paddocks. Thus, the average reading of each individual paddock used in the "pre/post" method is likely to be more accurate because it is based on a larger number of meter readings. In addition, any systematic error in the plate meter will have less impact with this method than with the weekly-based method due to the greater differences between 2 HM for each paddock (dilution factor).

Considering the combined data from the 3 years, the amounts of pasture grown annually were similar for the 3 systems (11.8 t DM/ha). However, accumulation rates were higher for the 100S system than for the 100A system during the summer 96-97, although the opposite was true during the following spring and summer. These differences between systems were consistent with the differences observed between the HAR of silage- and non-silage-paddocks (Fig. 2). Thus, despite the fact that all systems were managed by applying common grazing guidelines, a consequence of this management and the systems set up (i.e. stocking rates) was that larger areas were conserved as silage for the 100A system (mean of 3 years ± s.d. = 79 ± 9 % of total farm area) than for the 100S system (37 ± 7 % of total farm area). Consequently, the herbage accumulation characteristics of the silage-paddocks were more strongly represented in the 100A system.

Conserving pasture for silage can affect HAR both before and after harvesting the herbage. The higher rates observed for silage paddocks before harvesting during the 2 springs (Fig. 2) were the result of longer periods of undisturbed herbage accumulation and greater HM. A higher leaf area index can be achieved by undisturbed pasture when grasses are changing from the vegetative to the reproductive stage, due to the associated physiological and morphological changes that occur in the plants in early spring (Robson *et al.* 1988; Lemaire and Chapman 1996). This is also supported by a previous systems study in the UK, in which the amount of herbage metabolisable energy (ME) utilised from paddocks that were cut 3 times for silage was about 27 % greater (on average of 2 systems) than that of paddocks that were grazed (Leaver and Fraser 1989).

The effects of conservation on the HAR during the period following harvest depend strongly on the residual left after cutting and moisture availability. Average residual HM after cutting for silage conservation was about 1500 kg DM/ha in all years (about 4-5 cm of compressed height), a value that is within the limits in which HAR are negatively affected by the HM (Fig. 3). In Year 2, a brief period of moisture deficit followed the silage harvest in late October and reduced regrowth rates, but after sufficient rainfall in November (57 mm), the post-silage paddocks had significantly faster HAR than the non-silage paddocks, an effect that continued during the summer (Fig. 2). Higher HAR in summer and autumn have been observed in New Zealand for pastures that were allowed to grow for longer in spring before being grazed (late control) compared with the more traditional “early control” (Da Silva *et al.* 1993), an effect attributed to a greater tillering rate for the late-controlled pasture in the following season. However, this effect was not observed either in the other 2 seasons of the present study or in a separate 2-year whole system study which tested the above hypothesis (Bishop-Hurley *et al.* 1997), although difficulties in setting up and maintaining the experimental treatments were encountered in the latter study. This suggests that any carry-over effect of differences in spring pasture management, when present, will be the result of the interactions between several factors, including HM and time of cutting, grazing pressure on the rest of the farm area, and soil moisture, rather than simply the results of different spring grazing managements.

4.2. DM intake by the difference method and the n-alkanes method

A second objective of the present work was to investigate the effects of calving date systems on the seasonal herbage DM intake of cows, and 2 methods were evaluated for that purpose. Intakes of herbage DM followed a seasonal pattern and were strongly related to the levels of pre-grazing HM and herbage allowances. This was expected because of the decision guidelines used for grazing management, which were designed to achieve a balance between HAR and herbage demand in each week, using herbage allowance and pre-grazing HM as control factors. Therefore, area grazed per day and rotation length varied seasonally for all 3 systems as a consequence of the applied management and dependently on pasture growth rate but independently of the season of calving (Table 3). Herbage DM intakes increased linearly at 0.2 kg/kg increase in daily allowance, which is similar to the 0.18 kg/kg reported by Wales *et al.* (1999) for irrigated perennial ryegrass-white clover pastures in northern Victoria.

Herd estimates of herbage DM intakes by the difference method were generally higher than the average of individual cows' intakes measured by the n-alkane method (Table 3). This agrees with previous results reported by Reeves *et al.* (1996), who compared both methods against the calculated requirements for dairy cows grazing kikuyu (*Pennisetum clandestinum*) in Victoria. In contrast, Robaina *et al.* (1997) reported that intakes estimated by the n-alkanes method were 20% greater (an average of 2 experiments and a total of 12 different comparison of means) than those estimated by the difference technique, for ryegrass/white clover pastures in southern Victoria, which were generally of lower digestibility and grazed at higher pre-grazing HM than those used in the present study. Because the difference method measures the amount of herbage DM that has "disappeared" between a pre- and a post-grazing measures, rather than the amounts actually eaten by the cows, relatively higher estimates will logically be expected when using this method, as other factors (e.g. treading) also contribute to the disappearance of the DM, especially with higher pre-grazing HM. Nevertheless, in both studies (Robaina *et al.* 1997 and Reeves *et al.* 1996), as well as in the present study, intakes measured by the n-alkanes technique were in closer agreement with values calculated from energy requirements, than were the intakes estimated by the difference method.

Although neither method can "measure" actual intakes, the n-alkanes method is considered in the present study as the method of reference for 2 reasons. First, it has been validated with fresh herbage fed indoors (Dove and Mayes 1991; García *et al.* 2000a, Chapter 4) and has been widely used with grazing dairy cows (Reeves *et al.* 1996; Robaina *et al.* 1997; Buckley *et al.* 2000). Secondly, energy-based predictions of total DM intakes were in much closer agreement with the averaged results from the n-alkanes method (RMPE = 10.7%) than with the average herd intakes estimated by the difference method (RMPE = 23%), which agrees with previous studies (Reeves *et al.* 1996; Robaina *et al.* 1997). On average for all systems, values obtained by the difference method were 10 ± 23% higher, and those obtained by the n-alkanes method were 7 ± 7% lower, than calculated values (data from Tables 2 and 4). Fulkerson *et al.* (1986) reported that intakes measured by the difference method were slightly lower than the calculated values (95 ± 7 % of calculated values) for a 2-year study in Tasmania.

Nevertheless, the correlation between individual pairs of measured (n-alkanes) and calculated (energy-based equations) DM intakes, though highly significant, was only 0.48. However, the predicted values were based on only 1 measurement of milk yields by herd test, during the first week of each experimental period and on only monthly changes in cows' liveweights. Thus it is possible that better relationships between estimated and calculated values could have been obtained had the individual milk yields and liveweights been measured more frequently.

The efficiency of feed conversion, expressed as kg of milk fat + milk protein produced per kg of DM eaten (measured by the n-alkanes method), was greater in early lactation and lower in late lactation regardless of the calving season (Table 5). This result was expected as it is well documented that dairy cows partition relatively more nutrients toward the mammary gland than to body tissues in early lactation, and that this relationship reverts gradually as lactation progresses (Bauman and Curry 1980). For cows in mid lactation, however, those that had calved in the autumn had significantly greater conversion efficiencies than their spring-calved counterparts, which resulted in a significant interaction between system and time of the year. Although total DM intakes were similar between these 2 groups of cows, organic matter digestibility (and consequently, total digestible DM intake), were 10 units higher in September for the autumn-calved cows than in December for the spring-calved cows (Table 4). This difference in the concentration of ME between early and late spring (about 1.0 MJ/kg DM) represents an increase of approximately 18 g milksolids per kg of DM consumed (Holmes *et al.* 1987). In a companion paper that analysed and modelled the lactation curves of these autumn- and spring-calved cows, García and Holmes (2000) (Chapter 3) have shown that, in addition to the effects of their longer lactations, the greater total milksolids yields of the former cows were mainly due to their greater yields in mid lactation, which is consistent with the higher conversion efficiencies observed for those cows in the present short-time study. Nevertheless, the effect was not evident for the 50A cows, but the reasons for this are not obvious.

4.3. Intakes of maize silage DM by individual cows

The third aim of this study was to investigate the variation in DM intakes of maize silage by individual grazing cows supplemented as a group, while simultaneously evaluating the performance of the "n-alkanes & 13C method" which has been proposed for that purpose (García *et al.* 2000a, Chapter 4). The average daily intake of maize silage DM estimated by this method was lower than the average amount of maize silage DM actually offered to each herd. The daily allocation of maize silage was offered directly on the ground in the paddocks, a practice that inevitably resulted in some wastage of silage, which was not measured directly. Earlier work conducted in New Zealand (Wallace and Parker 1966) reported wastage of DM to be 25% and 5% respectively, when grass silage was fed either on the ground in the paddock, or in a covered yard. Similarly, wastage of silage DM offered to lambs in the UK was much lower when fed indoors (7-9%) than in the paddocks (31.4%, Liscombe Experimental Husbandry Farm 1977). If the silage wastage reported by Wallace and Parker (1966) were assumed for the present study (23%), then the intakes estimated by the "n-alkanes & ^{13}C method" would be very close to the average amounts actually eaten by the cows. Thus, silage wastage in the paddocks probably explains most of the discrepancy observed between DM actually offered to the cows and the estimated intakes, although the possibility of a slightly underestimation of intakes by the "n-alkanes & ^{13}C method" can not be completely ruled out.

The "n-alkanes & ^{13}C method" can also be useful to determine relative differences in silage and herbage intakes by individual animals. Even though the errors in the determination of herbage and maize silage digestibilities could affect the absolute estimates of intake markedly, the relative differences in the diet composition between individual animals would be less affected. Further, in both the original work by García *et al.* (2000a) (Chapter 4) and in the present study, the estimated values for maize silage DM intakes for the unsupplemented cows (control cows in the original work and all the 50A cows during the second week of Period 3 in the present study) were virtually zero, equal to their actual feeding management. This constitutes a partial validation of the method.

Large differences between individual cows in the daily intakes of maize silage DM were observed in the present study (Fig. 7). Only a few cows in both experimental systems had intake levels near the group-average and coefficients of variation were 30% and 49% for 100A and 50A cows, respectively. Similar results (coefficient of variation = 36%) were reported previously for autumn-calved grazing dairy cows offered the silage in troughs (García *et al.* 2000a, Chapter 4), and even wider variations between individuals has been observed for concentrate-fed sheep (Curtis *et al.* 1994; Holst *et al.* 1994). In the present study, however, the individual variation in maize silage DM intakes was positively related to the level of milk yield, whilst herbage DM intakes remained fairly constant between low- and high-producing cows (Fig. 8). These results are in direct contrast with those reported previously (García *et al.* 2000a, Chapter 4), in which the higher-yielding autumn-calved cows compensated for their greater requirements by consuming more herbage rather than more maize silage DM. However, herbage availability was more restricted in the present study (particularly for the 100A cows for which herbage allowance was only 25 kg DM/cow.day) and the amounts of maize silage offered per cow were considerable higher for that herd in the present study (9 kg DM/cow.day) than in the study by García *et al.* (2000a, Chapter 4) (4 kg DM/cow.day). Further, despite the fact that sufficient space per cow in the troughs (1.5 linear m) was provided in the latter study, cows were allowed to eat the silage for approximately 2 h only after the morning milking. The video-recorded behaviour of those cows (unpublished results) clearly indicated a strong dominance of some cows over the others, which might explain the lack of relationship between intake of silage and milk yields. These behavioural factors are less likely to affect intakes of individual cows when the silage is offered over relatively larger areas in the paddocks, with free access during the whole grazing period.

5. Conclusions

Systems that differed in calving dates, but to which the same basic grazing guidelines were applied, showed small but significant differences in HAR at different times of the year, which were attributed to differences between silage and non-silage paddocks. However, when all data were combined, total pasture production was very similar for the 3 systems. According to either the difference technique or the n-alkanes method, herbage DM intakes varied seasonally for all 3 systems, being higher when HAR was faster and lower when HAR was slower. Nevertheless, the difference method seems to overestimate herbage intakes, particularly during the spring season, and standard errors were relatively high for this method.

Although it is impossible to determine the exact performance of the "n-alkanes &13C method" in the present study, the method was successful in detecting the diet proportions of individual animals, and, if silage losses in the paddocks of about 25% are assumed, also the total amounts of maize silage eaten by the cows under normal farming conditions. Intakes of maize silage DM differed widely between individual cows, and this variation was partially associated with their level of milk production. The combined results from the present study and those from previous work (García *et al.* 2000a, Chapter 4) indicate that grazing dairy cows supplemented with maize silage seem to be able to adjust for their different requirements (i.e. production level) by increasing the DM intakes of either herbage or maize silage, whichever is less restricted. This has an important practical application as dairy managers in Australia and New Zealand could avoid potential losses in production when offering maize silage to cows grazing restricted pasture by, for example, increasing the silage accessibility in terms of either feeding time of feeding space.

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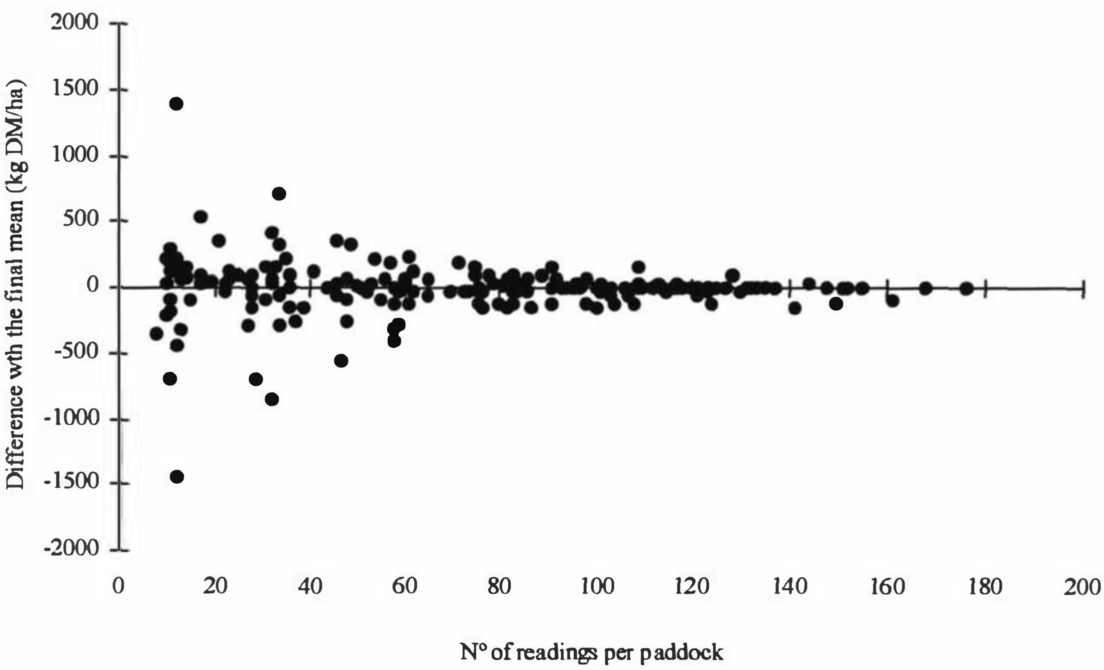
Appendix

Rising plate meter and number of readings per paddock. The graph shows how increasing the number of readings per paddock (up to about 100 readings) reduces the effect of random variation on the final average herbage mass (unpublished results).



Overview of Chapter 6

In Part II, an innovative combination of methods for estimating herbage and maize silage DM intakes by individual grazing cows has been presented and validated (Chapter 4), and re-evaluated with an independent set of data (Chapter 5). Overall, the methodology proved useful for its objectives and exposed the large variation in the intakes of maize silage DM by individual animals under different systems of supplementation.

Chapter 5 also showed that the application of common management guidelines to three systems with very contrasting calving dates resulted in similar values of herbage accumulation rates and intakes for all three systems, except for some small differences in spring and early summer.

Overall, Part II has helped to provide an understanding of some of the complex variables of the real-world systems. The integration of methodologies in a form of a dynamic, interactive, whole-system model is the aim of the last part of this thesis, Part III. The development of such a model is the topic of Chapter 6.

Part III

Modelling Studies

Chapter 6

IDFS: a dynamic Interactive Dairy Farm Simulator

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Abstract. Available whole-farm models do not allow the user to interact and make decisions while running the simulation. Therefore, these models do not resemble the actual continuous decision making processes that take place in real farms. The objective of the present study was to develop a model capable of representing the main components of seasonal dairy systems in an interactive and dynamic way, allowing the user to evaluate the application of different decision rules and decision-making policies on the performance of different calving systems. The model is a mathematical, dynamic, deterministic (although some inputs can behave stochastically), and mechanistic model that has been called Interactive Dairy Farm Simulator (IDFS), and was developed using the commercially available software Stella Research 5.1.1. Seasonal systems are defined by the stocking rate, planned start of calving date, and calving pattern. In addition, the HAR, herbage digestibility, and herbage crude protein contents, are inputs. The user must make continuous decisions during the simulation regarding which of 10 paddocks will be grazed, with which cows, when paddocks will be grazed again, which residual HM the cows will leave on each individual paddock, how much supplement will be fed (and of what type), etc. The model first calculates the cows' potential intake (given by animal-related factors). Potential intakes are then affected by herbage availability and quality (relative intake), resulting in the actual daily intake rates. Dry matter intakes are then converted to metabolisable energy (MJ/kg DM), which in turn determines milk yields after accounting for maintenance requirements. However, any shortage in crude protein intake (either degradable, non-degradable in rumen, or both) will limit milk production and prevent the potential (i.e. the yields given by the availability of energy) from being achieved. In summary, IDFS is a dynamic simulator of a seasonal dairy farm that enables, at present stage of development, management of the main components of a real pasture-based dairy farm to be simulated.

Keywords: dairy farm; simulation; modelling

1. Introduction

Calving season and calving pattern are key factors of the seasonal, pasture-based dairy farms in New Zealand (Chapter 1). Change in the season of calving will have effects not only at the farm level, but also will have implications for the processing factories. Some of these effects can be evaluated by means of whole-farm systems research (Chapter 2), in which contrasting calving systems were studied by applying a common set of management guidelines. However, the number of system hypotheses that can be tested in these real systems is limited by resources and time.

For any researcher who is interested in studying relationships and interactions at the whole farm level, the ideal situation would be to work with a 'whole-farm-model' that can represent the key components of real systems (i.e., farms) with relative accuracy (see Sherlock *et al.* 1997). The investigator would then be able to use the model to design and run an unlimited number of 'computer-experiments', with the obvious advantages in terms of saving time and resources. However, when a real dairy farm system experiment is set up and carried out, the trial is not just launched and the results observed at the end of, for example, one calendar year. Instead, decisions related to both daily routines and experimental objectives, are made regularly by the research team in order to accomplish the original objectives successfully. It follows that the model should allow decisions to be made by the researcher, as is the case in the real field experiment. By doing so, the model will not only be a closer representation of the real world, but it will also include the factor largely ignored in most models: the human management factor.

The objective of the present study was to develop a model capable of representing the main components of seasonal dairy systems in an interactive and dynamic way, allowing the user to evaluate the application of different decision rules and decision-making policies on the performance of different calving systems. It must be emphasised that, although a minimum degree of realism was required, the model was not intended to cover each and all the factors and interactions that take place in a real farm. The complexity required for such a model is beyond the scope of this project and, as Cacho *et al.* (1995) pointed out, the "...risk of getting lost in the complexity of the system being represented is ever-present."

The model constitutes an interactive, highly dynamic tool for simulating the key components of seasonal, pasture-based dairy farms, and it was therefore called ***IDFS*** (interactive dairy farm simulator).

2. Model overview and classification

Overall, the IDFS deals only with the main components of seasonal pasture-based dairy systems, including calving date and calving pattern, stocking rate, herbage growth, herbage intake, and the conservation and feeding of supplements.

In IDFS, the system's behaviour is represented by a set of mathematical equations, which means that the model can be categorised as a *mathematical model* (France *et al.* 1987). According to the model classification given by these authors, the IDFS is a dynamic model in which all equations are recalculated on a daily or even hourly basis. It is also deterministic, although one of its key inputs, herbage accumulation rate (HAR), can be "switched-on" to behave stochastically. Finally, because the behaviour of the whole system is analysed by modeling its main components and their interactions, the model can be regarded as mechanistic in nature (France *et al.* 1987), despite the fact that many relationships within the model are empirical.

The IDFS model is an interactive tool that can be run in a totally manual or in a semi-automatic mode, but which always needs management decisions to be taken by the user. This was a deliberate design-characteristic because one of the main limitations of existing whole farm programs (e.g. UDDER [Larcombe, 1989]) is that the user is not allowed to interact with the model while the simulation is running. Thus, the present model incorporates the decision-maker as a key factor of the farms' components. Just as real farms need the staff to make decisions 'on the ground', the IDFS needs a decision-maker to 'run the farm'. Thus, just as real farmers decide, by opening and shutting the appropriate gates, when the cows will graze a given paddock and when they will be moved to another paddock, the IDFS allows the operator to perform those tasks, simply by making decisions through input tables, graphs, and other control devices.

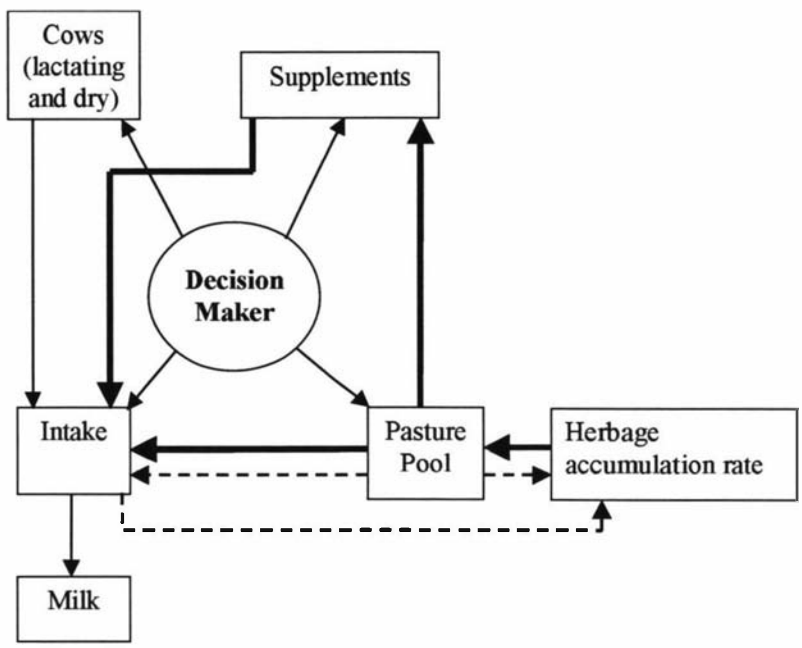
In actual farms, decisions are made daily at some times of the year; for example, when supplements are being fed out and every day the farmer must decide the amount to be offered to the cows, or when cows need to be shifted from one paddock to another daily. At other times of the year, however, farmers will do their daily routines (e.g. milking), but decisions (i.e. changes) will be taken in a more relaxed time frame. Running a dairy farm with IDFS is very similar: the operator will make decisions sometimes on a daily (or hourly) basis, and sometimes every few (simulated-) days.

3. Model description and features

The model was completely developed by the author of this thesis using the software Stella Research version 5.1.1, and based on an author's original idea. The software is a graphical programming language which has been designed specifically for creating continuous-time dynamic models for research and teaching (Hannon and Ruth, 1997).

In essence, IDFS simulates the physical performance of a pasture-based seasonal calving system for any period of time selected by the user (i.e., from a few hours to several years).

Fig. 1. A schematic representation of the IDFS model. Flows of material, information, and feed-back mechanisms are represented by heavy-solid lines, light-solid lines, and broken lines, respectively.



A schematic representation of the IDFS model is presented in Fig. 1. At any given time during the simulation, feed is made available to the "pasture-pool" as a consequence of the HAR. Outputs from the pasture-pool are determined by the total actual intake rates, which in turn are dependant on the number and characteristics of lactating and dry cows (i.e., potential intake) and the availability of herbage (i.e., relative intake). Supplements may cover the intake demand at any rate when stipulated by the user. Fig. 1 highlights the central role played by the user (decision-maker), who can 'control' and influence all the key factors of the model at any time during the simulation.

Milk is "produced" in IDFS as a result of the total energy and protein available after maintenance requirements have been covered.

In practice, herbage factors are represented by a set of individual paddocks, and cow-related factors occur at a herd level, both of which are described in detail below.

3.1. Paddocks

There are up to 10 individual paddocks in the simulated farm. The user can easily modify the size of each paddock (from one of the input tables), and by simply reducing their areas to zero can decrease the number of total paddocks.

Net herbage accumulates on each paddock according to a general curve of net HAR. This might be seen as a limitation of the model, because in reality, paddocks
57 differ in their potential (soil-types, fertility-levels) to grow~~th~~ pasture. However, although based on a 'general' curve, the accumulation rate on each paddock remains individual and is affected by grazing on an individual basis too (see below). This allows, if desirable, the inclusion of individual growth rates for each individual paddock. Alternatively, the model can be switched-on to allow the growth rate inputs to be stochastic. By doing so, the general curve, for each particular day of the year, will take a random value according to a predetermined probability function. Finally, the user can easily change the general growth curve just by double clicking into the graph-input, editing, and modifying the curve or its values. The latter option allows the researcher to quickly investigate the effect of, for example, a dry summer on the whole system.

3.2. Cows

In New Zealand, the majority of the commercial dairy farms have a compacted calving season that starts 283 days after the first day of the breeding season, the duration of which does not exceed a 10- or 12-week period. Similarly, in IDFS the dairy cows are represented by up to 12 different herds or mobs. Each mob comprises the groups of cows that calve during a particular week of the calendar year. For example, if calving starts on 1 August, and 5% of the total herd is expected to calve during the first week, the mob = *Week1* will comprise *Total N° of Cows* (i.e. *Stocking rate* × *Total area*) × *0.05*. It is assumed that all the cows in each mob calve on the first day of the week.

Calving date and calving pattern are specified by the user. The IDFS simulates a seasonal farm; therefore, the main driving force in the model is the planned start of calving date (PSC), just as is the case in a real seasonal farm. The user may also include his or her desired pattern of calving by specifying the proportions of cows that will calve in each of the 12 weeks following the PSC. By setting the proportion of calved-cows to zero for a particular week, that 'mob' will no longer exist for the model calculations. Thus, calving pattern can be specified (if desirable) as 100% occurring in the 1st week of the calving season, or as any other combination of proportions within the total 12-week period.

Once calved, every cow within each group of cows which constitutes a 'mob' will have the same potential and relative intake rates, energy and protein requirements, live weight (LW) gains or losses. Consequently, those cows within each mob will have the same total daily DM intake and milk production. Therefore, for each particular day of the calendar year, and provided there are lactating cows in the simulated farm, the average total daily DM intake, energy and protein requirements, LW changes and milk yields will be the "weighted" mean of the 12 mobs. It is important to note, however, that despite the fact that the 'average' output will be the factor of interest in most cases (as is, for instance, total daily milk production in the real farm), the structure of the model allows information to be obtained from the 'individual' mobs, which calved at different dates. Thus, different requirements and outputs can be computed for cows that have calved early in the season and their performance can be compared with their counterparts that have calved later in the season.

Because each of the 12 mobs is considered in the model as an individual entity, the drying-off pattern can also be specified 'individually' for each mob. This is an important difference from UDDER, in which the cows furthest advanced in the lactating cows' group are always the ones that are dried-off first. Therefore, lactation lengths need to be calculated by multiplying each day of the year in which there is at least one lactating cow by the number of lactating cows on each day. Unless otherwise stated by the user, the IDFS model assumes that each and all the individual mobs (and thus, every cow in the farm) will be milked for 305 days. This is of course not true in reality and an important feature of the IDFS is that individual mobs (or even individual cows!) can be dried-off whenever the decision-maker decides to do so. "Individual" cows may be dried-off (or culled), by representing the appropriate proportion in the input table. For example, in a 100-ha farm with 300 cows in milk in which 20% of the total cows have calved in the 2nd week after the PSC, drying-off 5% of that mob will reduce the total number of cows by 3 (60 ×

0.05). It is important to emphasise that those cows will be taken off from the selected mob (from the 12 available) and not from any other mob.

4. How IDFS works

In essence, the way the model functions can be described as follows (Fig. 2): at any particular time during the simulation there are either lactating cows, dry cows or both (depending on the PSC date and the period of time being simulated), which determine the potential total intake by the herd. For each week during the calving period, the number of lactating cows (L) is given by:

$$L_{(t)} = L_{(t-dt)} + (R-D)dt \tag{1}$$

where R and D are respectively the calving and drying-off rates specified by the user and dt is the interval time.

4.1. Potential intake

If the cows are lactating, their potential intake will be a function of several factors including age, standard weight at maturity, actual weight, and in particular, stage of lactation. The equation used (SCA 1990) was:

$$\mathrm{PI_i} = (\mathrm{jWS}(1.7\text{-}\mathrm{S}))\mathrm{m_I} \tag{2}$$

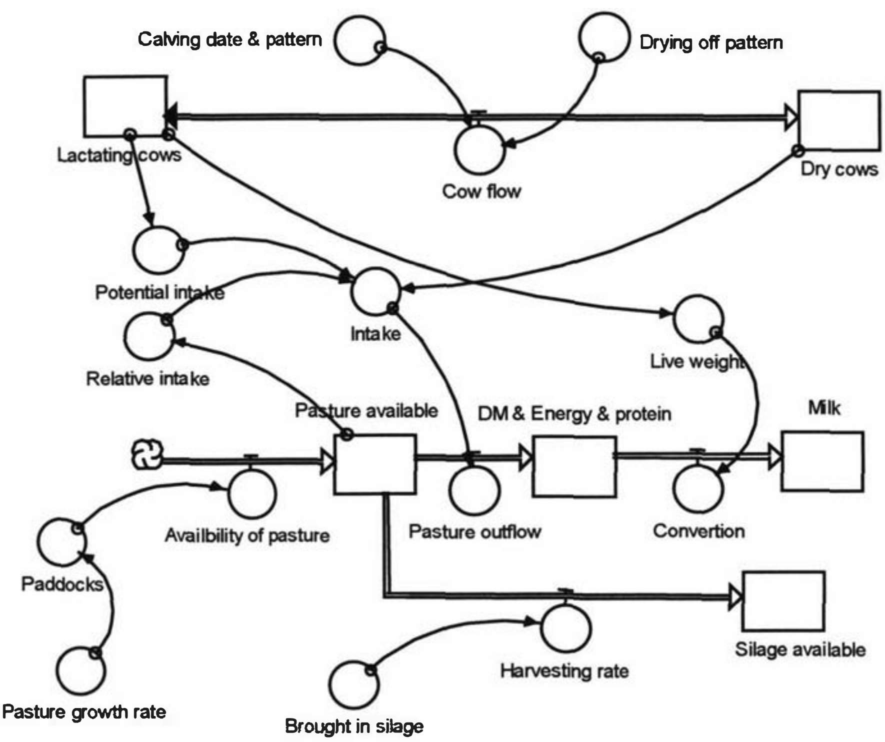
where PI_i is the potential intake for the group of cows calved in week i, j is a constant, W is the standard reference weight, S is the relative size (see SCA 1990 for definitions) and m_i is a factor which depends strongly on the stage of lactation and is given by:

$$m_i = 1+a(DIM_i)^{1.7e(-0.021(DIMi))} \tag{3}$$

where a is a constant and DIM_i is the number of days in milk for cows that calved on week i. Because this factor represents the main driving force for the cows' potential intake, and so their genetic merit, differences in the latter may be simulated simply by multiplying factor m by numbers greater (to increase the genetic merit) or lower (to decrease the genetic merit) than 1. Such a multiplier factor would assume that productive differences in genetic merit are uniformly expressed during the whole lactation, as supported by data from Dillon and Buckley (1998).

If the cows are dry, their potential (and total) intake is determined directly as an input by the user. This was adopted because in reality, dry cows in New Zealand dairy farms are usually restricted in their intake levels.

Fig. 2. A simplified diagram of the IDFS model.



4.2. Relative intake

The average potential intake is then multiplied by the relative intake, a factor that depends on both the relative availability of herbage and also on other factors such as herbage digestibility and % of clover:

$$RI = AC(1-h(0.8-D)+0.17c \qquad (4)$$

where *RI* is relative intake (range 0 to 1), *A* is the relative availability of herbage (see below), *C* is the relative capacity of the animals (=1), *h* is a constant, *D* is the *in vitro* DM digestibility and *c* is the proportion of clover in the pasture.

These intake relationships follow the equations proposed by the SCA (1990), although the mechanistic model of Woodward (1997) has been incorporated to calculate the relative availability of herbage. Woodward's (1997) proposal was to estimate total daily DM intake (DI) using a Michaelis-Menten response function, as follows:

$$DI = \frac{\left\{(1440 - t_i)\dfrac{BW_{\max}}{t_p + BW_{\max}(t_m + t_r)}\right\}HM}{\left\{HM_{1/2}\dfrac{t_p}{t_p + BW_{\max}(t_m + t_r)}\right\} + HM} \qquad (5)$$

where t_i (m/day), t_p (m/bite), t_m (m/g DM) and t_r (m/g DM) are the times cows spend on idling, prehension, mastication and rumination activities, respectively; BW_{max} is the maximum bite weight (g/bite), HM is the herbage mass and $HM_{1/2}$ is the HM at which BW is $0.5BW_{max}$.

Although this model alone can be used to estimate herbage DM intake, the IDFS model follows the approach of estimating intake by combining potential intake (given by animal factors) and relative intake (given by herbage availability and quality) (see Herrero et al 1998 for a review). However, instead of combining potential intake with an empirical relationship for relative intake, the previous model of Woodward, which is more mechanistic in approach, was used to estimate the relative availability of herbage. Thus, if the expression in brackets in the numerator of equation (5) is called (a) and the expression in brackets in the denominator is called (b), relative availability (A) of herbage for equation (4) was calculated in IDFS as:

$$A = \frac{\dfrac{aHM_i}{b + HM_i}}{\dfrac{a4000}{b + 4000}} \qquad (6)$$

where HM_i is the HM (pasture cover) of paddock i and the number *4000* represents an arbitrarily selected HM, at which herbage intake is unlikely to be limited. As the cows graze down paddock i, HMi, and consequently the numerator of equation (6) decrease, and A (which varies from 0 to 1) approaches zero. Nevertheless, it is noted that all these equations that determine the relative intake can be overridden by entering the desired value in the appropriate input table before starting the simulation. For example, entering the unit will mean that total actual intakes are exactly the same as the potential intakes.

4.3. Herbage mass and herbage accumulation rate

Cows graze the paddock stipulated by the user, until he or she decides to move them to another paddock. This means that the user can determine what the pre and post-grazing HM will be for each individual paddock, and most importantly, those values may differ if for example, dry cows are forced to graze a particular paddock very hard. The amount of herbage DM being grazed down is given by the total daily intake per cow and the daily stocking rate.

It is important to note that the model is highly dynamic: herbage grows continuously even in the paddock that is being grazed at the moment (as occurs in reality), and the rate of 'regrowth' is affected by the grazing intensity (once again, as in reality). This was done by including, for each individual paddock, the logistic equation:

$$\frac{dHM_i}{dt} = rHM_i(1 - \frac{HM_i}{HM_{\max}}) \qquad (7)$$

where HMi is the herbage mass of paddock i, r is the maximum relative growth rate and HM_{max} is the HM at which net accumulation rate approaches zero because senescence rate approaches gross growth rate (HM_{max} is also called "ceiling yield"). Although this HM_{max} will vary seasonally (Cacho et al 1995), in the present model it was arbitrarily set to 4500 kg DM/ha, until appropriate local data are available. For each day of the simulated year, r is the HAR entered by the user as an input and actual HM for paddock i is given by:

$$HM_i = HM_{i(t-dt)} + (r_{i(l)} - h_i - DMI_l - DMI_d)dt \qquad (8)$$

where $r_{(l)}$ is the growth rate r affected by the previous logistic function (equation 7), h is the harvesting rate (in case silage is being made from paddock i), DMI_l and DMI_d are the daily intake rates when either lactating, dry or both types of cows are grazing paddock i, and dt is the differential time.

4.4. Supplements

Supplements can be introduced to the cows at any time. Supplements substitute herbage at a rate stipulated by the user. In addition, the user may also restrict the intake of herbage by setting the maximum amount of herbage to be consumed by each individual cow. This overrules all other relationships in the model in terms of the outflow rates of herbage from any particular paddock. This was included because in the real farm, herbage intake is usually limited during winter (further than it is by the use of supplements) to avoid decreases in either the average HM and/or pre-grazing HM to values below desirable levels.

4.5. Liveweight

At the present stage of development, the model considers changes in cows' live weights (LW) according to a 'standard' LW curve, which starts at calving. This LW curve can be set up individually for each of the 12 lactating 'mobs', although the same curve for all mobs is given by default. Thus, following calving, cows lose weight down to a minimum and then regain weight in accordance with the 'standard' input curve. Although it is acknowledged that, in reality, this depends on genetic merit, milk yield, and level of feeding after calving, it should be remembered that the model does not intend to predict all the relationships and interactions that take place in a real farm with high accuracy. It does intend, however, to provide the researcher with a relatively simple, although highly dynamic, tool, which enables him or her to investigate the impact of decision making on the more general aspects of the dairy farm.

As a result of this 'standard' input curve, the pool of total Metabolizable Energy (ME) available for maintenance and milk production will be increased by extra energy coming from tissue mobilisation when cows are in negative energy balance (i.e. from calving up to the point of minimum LW). Conversely, the pool of total ME available will be decreased by the amount of energy required to regain the original LW when cows are in positive energy balance (i.e., from point of minimum LW up to drying-off date).

4.6. Energy requirements and milk production

The pool of Total ME eaten determines the amount of milk that will be produced. Energy is used for maintenance first, and the difference between total energy consumed and energy used for maintenance (± energy from LW changes), is used for milk production (no energy is accounted for pregnancy at this stage of development). All the equations in terms of energy use and energy partitioning are based on SCA (1990), as follows:

$$MEm = [(KSM\,0.26LW^{0.75}e^{-0.03age})/km] + [Egraze/km] + [PID_p 0.09] + [SppID_s 0.09] \quad (9)$$

where K,S,M are constants, LW is the actual liveweight, km is the efficiency of energy used for maintenance, *Egraze* is an additive factor which accounts for the energy spent on the grazing activity, *PID* is the amount of digestible herbage DM eaten and *SppID* is the amount of supplement digestible DM eaten.

Thus, maintenance requirements depend mainly on the cows' LW, although other factors such as total daily energy intake and energy spent in grazing activity are also taken into account. The factors (last two terms of equation [9]) accounting for total intake of energy are particularly important, as their inclusion indicates the acceptance that maintenance requirements are not 'fixed' but vary accordingly to the level of milk yield (total energy intake).

Milk is produced as a result of the total energy available, considering 4.8 MJ ME/lt (SCA, 1990). However, the simple Rumen Degradable – Rumen undegradable protein system (RDP/URP) has also been included in the model. The concentration of crude protein in the herbage is given as an input[1], as is the protein concentration in both the silage made on the farm and the silage purchased. Therefore, at any time during the simulation, if the protein requirements (to produce the amount of milk stipulated by the 'energy availability') exceed the total daily protein intake (either RDP, URP or both), daily milk yield will be limited by the equivalent of that amount of protein. In the graphical output form, two curves, which are superimposed on each other if protein is not limiting, will grow separately during the course of the simulation (i.e. the 'potential' and the 'actual' yield) to easily inform the operator about what is happening in the simulated farm.

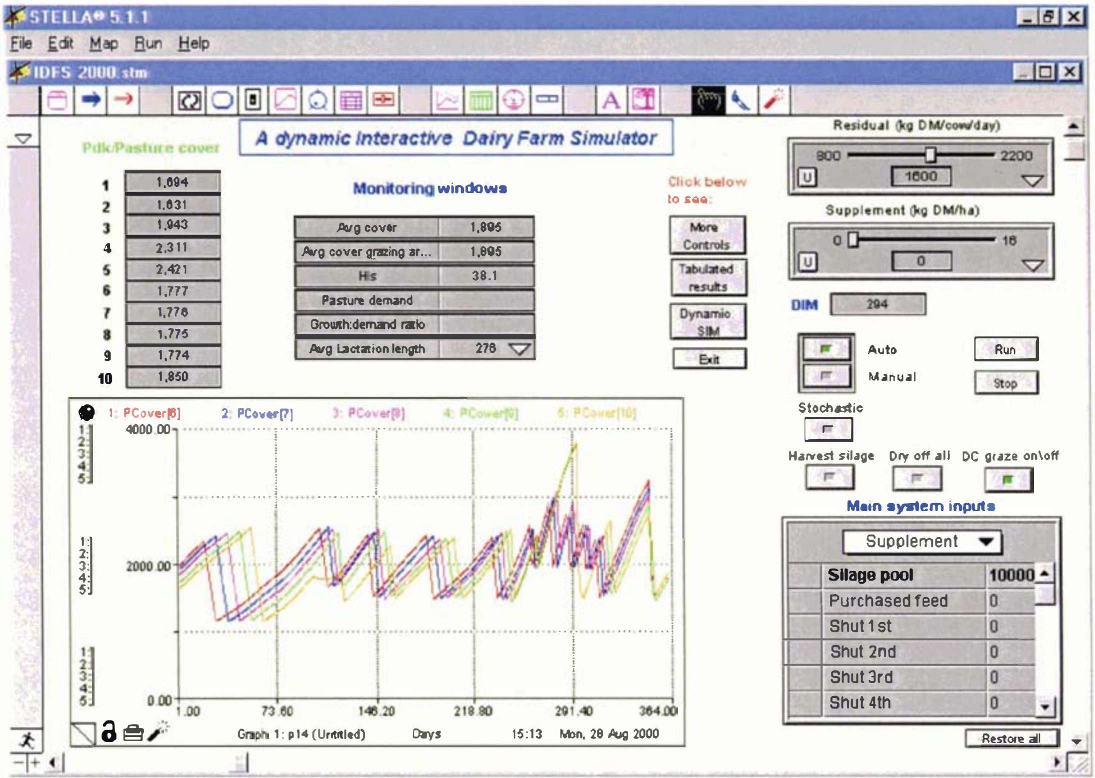
5. Running IDFS: an example

IDFS has 3 main interchangeable screens for user-interface, which are shown in Fig. 3, 4-5 and 6. Inputs are entered in these screens by selecting the appropriate tables, graphs, switches, knobs, or slides. The control set of the first 2 screens is exactly the same and will suffice for most common circumstances. If needed, however, the third screen (Fig. 6) provides access to more detailed control of the

[1] Values of pasture Crude Protein concentrations (and all other similar inputs such as pasture DM digestibility) for the whole year can be entered using a graph form (continuous line) or as values in a table.

model's features. Screens 1 (Fig. 3) and 2 (Fig. 4 and Fig. 5) also provide visual outputs that are indispensable in order for the user to make adjustments and decisions while running a simulation.

Fig. 3. Screen 1 of IDFS (details in text)



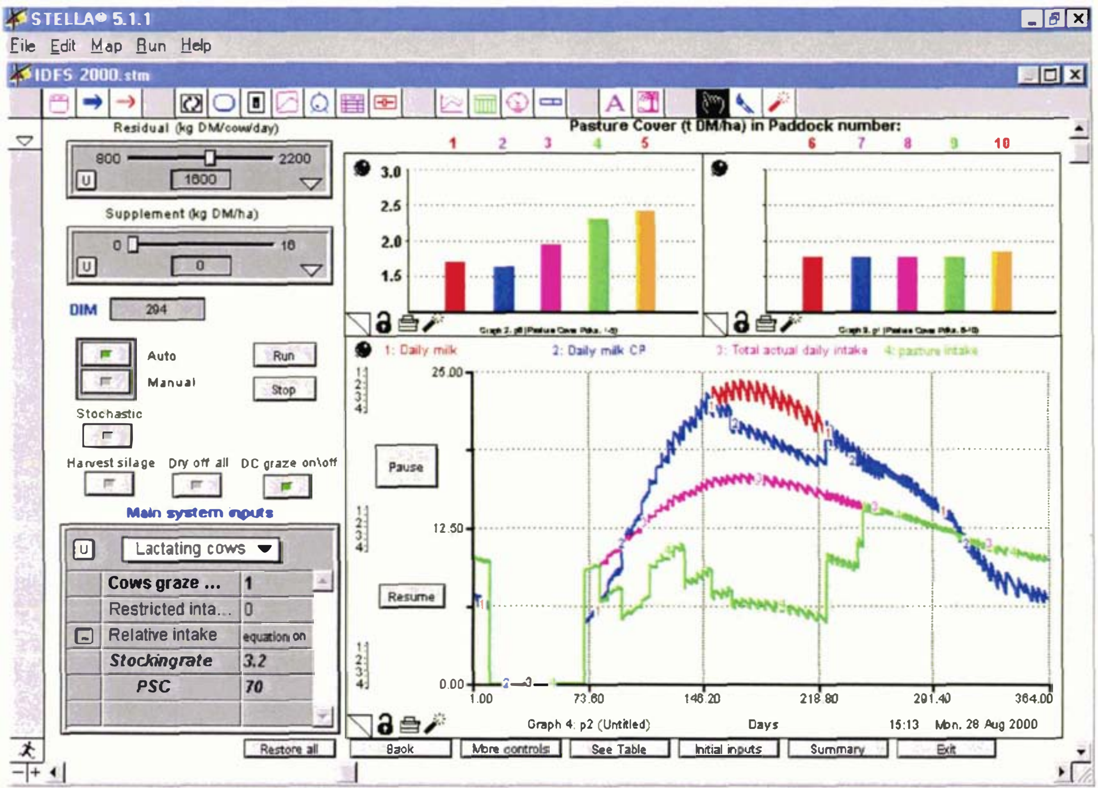
The first task for the user prior to running a simulation is to define the system. The system is defined basically by the PSC, stocking rate, the calving pattern (proportion of cows calved in each of the 12-week calving periods) and whether or not the dry cows will be maintained 'on-farm' (and fed) during the dry period. Stocking rate and PSC are entered in the input table at the bottom left of screen 2. This table has 4 interchangeable sub-tables for inputs regarding the management of 1) lactating cows, 2) dry cows, 3) supplements feeding and conservation, and 4) the sequence in which the paddocks will be grazed when the semi-automatic mode is on. By default, individual paddocks have initial HM that range between 2500 kg DM/ha (paddock 1) and 1600 kg DM/ha (paddock 10), although both the initial values of HM for each paddock and the order in which they will be grazed can be modified (the former prior to the simulation only) from the input tables.

Once the system and the time frame of the simulation have been defined (the latter from the software menu), the simulation is launched by pressing the "RUN" button (screen 1 or 2). While lactating cows are present in the 'farm', the simulation can be run in the semi-automatic mode. This is the default option and is indicated by a green light in the switch labelled "AUTO". However, when lactating cows are being dried-off, either automatically by the model or manually by the user (by a click on the "DRY OFF ALL" switch), the model must be switched to MANUAL mode and maintained in this mode until calving has started and there are lactating cows grazing paddocks. At any time, and regardless of the mode being used, the simulation can be paused to allow decisions to be made. This is done by clicking the PAUSE button in either screen 1 or screen 2.

Fig. 4. Screen 2 of IDFS: the recommended option for running simulations (details in text).

Screen 2 is the recommended option for running a simulation. Two small coloured bar charts at the top of the screen offer a highly dynamic representation of the amount of HM present on each of the individual 10 paddocks at all times. That is, as the simulation proceeds, the user can see how the bar corresponding to the paddock being grazed decreases, while all the others increase in size (i.e., in HM) according to the corresponding HAR. The bigger graph at the bottom of the screen constitutes the key output-interface for decision making. This is because this latter graph provides continuous information of the current state of 1) the average HM in the whole farm, 2) the average HM in the grazing area (total farm area-area closed for silage harvest), 3) the HAR, 4) herbage DM demand, and 5) the milk yield per cow. By clicking at the bottom left of the graph, the figure is replaced by another graph (see Fig. 5) which provides additional information about the evolution of the total actual intake per cow, and herbage and supplement intakes. In addition, if dietary protein, either total degradable or non-degradable in the rumen limits milk production, the actual and potential yields are shown in this latter graph.

Fig. 5. Screen 2 of IDFS showing an example of how dietary protein may affect milk production (details in text).

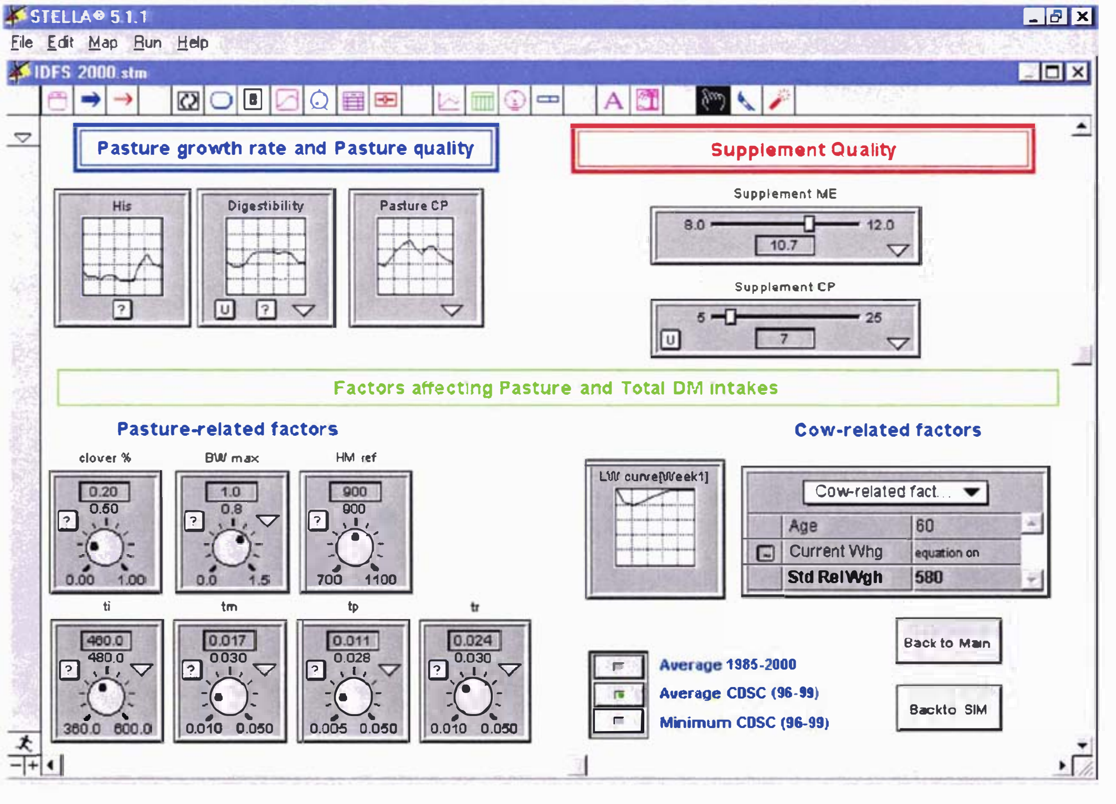


The graphs in Fig. 3, 4, and 5 show the results of a 365-day simulation of a 100% autumn calving system stocked at 3.2 cows/ha. Planned start of calving was 11 March (Julian date = 70). All cows were dried-off when the group of first calvers achieved 305 days in milk and all dry cows were grazed on farm.

The simulation was run with the central objective of maintaining the average HM at about 2000 kg DM/ha. If HM decreased below target, maize silage (10.7 MJ ME/kg DM and 7% Crude Protein) was fed to the cows in the quantities required to maintain the HM at its target value. Conversely, if HM increased over 2300 kg DM, individual paddocks were removed from the grazing area (closed) for future silage harvesting.

In order to illustrate the model capabilities, post-grazing residual HM was changed several times during the simulation by using the slide provided for that purpose at the top left of screen 2. These changes can be appreciated in the graph of Fig. 3, which shows the evolution of the HM of 5 paddocks (paddocks 6 to 10). These paddocks were first grazed by the dry cows down to a post-grazing HM of 1200 kg DM/ha. After allowing to regrow to about 2500-2600 kg DM/ha, paddocks were grazed down to 1700 kg DM/ha by the recently calved cows. Residual levels were reduced to 1500 kg DM/ha for the next 3 grazings (winter), and were lifted back to 2000 kg DM/ha during the spring. Paddock 10 was closed for silage, allowed to achieve almost 4000 kg DM, and harvested (together with other paddocks not shown in the graph) for silage, leaving a residual of 1500 kg DM/ha. The five paddocks were closed for a second cut of silage and harvested all together in late spring. The two peaks in HM occurring later in the year were a consequence of herbage surplus during springtime. Thus, the sharp drops of HM after each peak (pink line, Fig. 3) are the consequence of silage making. Only when one or more paddocks are closed for silage (not grazed), the average HM in the total and grazing area differ (pink and green lines, respectively).

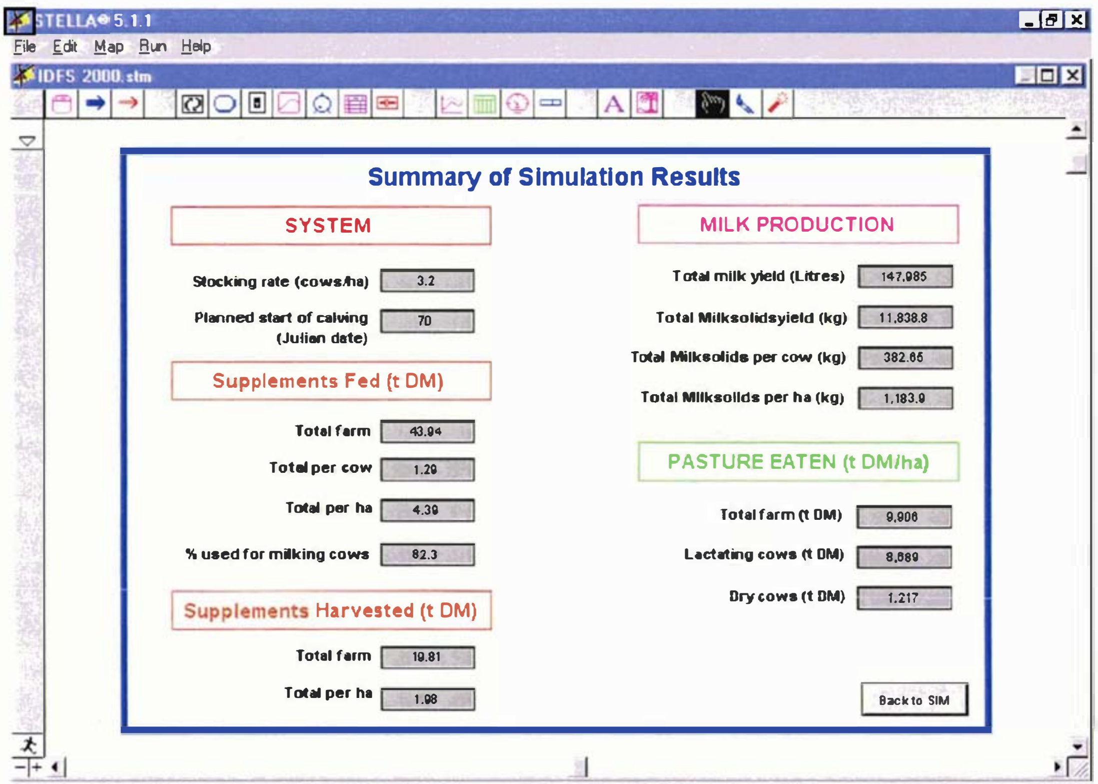
Fig. 6. More controls (less frequently used) in IDFS.



The graph at the bottom of screen 2 (Fig. 4) shows how the pasture demand (red line) was adjusted during the course of the simulation by feeding maize silage in order to maintain the HM (green line) at its target. The amount of supplement to be fed per cow on a daily basis is inputted from a slide provided at the top left of screen 2 (below the control of post-grazing residual HM). Due to the relatively high stocking rate selected for the example, this meant that cows had to be supplemented with up to 10 kg silage DM/day. This high level of low-protein feed in the diet of cows resulted in a protein deficit (of rumen undegradable protein in this example) and a consequent drop in milk production between days 151 and 222 (Julian dates), which is represented by the differences between the red curve (potential milk yield) and the blue curve (actual milk yield) in the graph at the bottom of Fig. 5.

The "saw-shaped" curves illustrate the dynamism of the model. In other words, because the model is highly dynamic, simulation results are not smoothed. Thus, herbage intakes, and consequently, milk production, are higher when the cows enter the paddock and the potential intake is not restricted, but both decrease within days or hours, when herbage availability restricts intake.

Fig. 7. A screen showing the summary of the main results from the simulation.



Screen 3 (Fig. 6) provides more detailed controls over the simulations. The 3 graphs at the top left are actually input-graphs for annual HAR, herbage digestibility, and herbage crude protein (from left to right, respectively). These graphs are useful tools provided by the software to rapidly change values between

simulations without losing the actual defaults in the model. The slides at the top right of the screen 3 allows the selection of the average chemical composition (energy and crude protein only) of the supplement fed to the cows. These values can be modified at any time during the simulation, allowing the effect of "different" supplements to be evaluated if desired. On the bottom right part of the screen some cow-related factors such as age, standard reference weight, current weight, etc. can be modified in an input table. Additionally, the standard curve of annual liveweight change can be modified from an input-graph. Finally, the 7 knobs at the bottom left of the screen give full control of the factors affecting primarily the relative intake.

A summary of the main results of the simulation is given in a fourth screen (Fig. 7). This screen contains information-windows for the key aspects of a dairy farm such as the characterisation of the system (by the stocking rate and PSC), the milk produced, the supplements fed and harvested, and the amount of herbage consumed by the cows. For example, the results of the simulation utilised as an example indicate that cows produced 382 kg milksolids per cow (1183 kg/ha), grazed 9.9 t DM herbage per ha, ate 4.4 t DM maize silage per ha, and only 2.0 t DM/ha was harvested as grass silage.

6. Final remarks

IDFS is a dynamic simulator of a seasonal dairy farm that enables, at present stage of development, the main components of a real pasture-based dairy farm to be simulated. It main feature is that it simulates the management decision and processes required to "run a farm". IDFS can simulate, for example, the impact of HAR on the whole system, the effects of different decision rules in terms of HM, pre- and post-grazing residuals, the effects of stocking rate and calving season, calving date, and calving pattern. The simulation of some of these effects using IDFS is the central topic of Chapter 7.

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Glossary of abbreviations

Term	Description	Unit
A	Relative availability of herbage	0-1 (equation)
BWmax	Maximum bite weight	g/bite (constant; default = 1)
C	Relative (intake) capacity of cows	0-1 (constant; default = 1)
D	Drying-off rate in any of the 12-week calving period	0-1
D	In vitro DM digestibility of herbage	0-1 (input)
DI	Total daily DM intake	Kg/cow (equation)
DIM	Days in milk	Days
DMI	Daily rate of DM intake	Kg/cow (equation)
Egraze	Additive factor for energy spent while grazing	(equation)
HAR	Herbage accumulation rate	Kg DM/ha.day
HM	Herbage mass	(kg DM/ha)
IDFS	interactive dairy farm simulator (the name of the model)	
km	Efficiency of ME used for maintenance	(equation)
L	Lactating cows	
LW	Live weight	Kg
m	The lactation factor for intake	Min=1
ME	Metabolisable energy	MJ
PI	Potential intake	Kg/cow.day
PID	Intake of digestible herbage DM	Kg/cow.day (equation)
PSC	Planned start of calving	Julian date
R	Calving rate in any of the 12-week calving period	0-1
RDP	Rumen-degradable protein	g (equation)
RI	Relative intake	0-1 (equation)
S	Relative size (relationship between actual weight and W)	0-1 (equation)
SppID	Intake of digestible supplement DM	Kg/cow.day (equation)
ti	Idling time	m/day (constant; default = 460)
tm	Mastication time	m/g DM (constant; default = 0.017)
tp	Prehension time	m/bite (constant;

Term	Description	Unit
		default = 0.011)
tr	Rumination time	m/g DM (constant; default = 0.024)
UDP	Rumen undegradable protein	g (equation)
W	Standard reference weight (weight at mature skeletal size)	Kg (constant; default = 580)

Overview of Chapter 7

The dynamic interactive dairy farm simulator (IDFS) developed in this thesis was described in detail in Chapter 6. Overall, Chapter 6 has shown how the IDFS was developed, how it works, and how it is run. Further, it has also shown how the model simulates the management decisions and processes necessary for "running a farm".

The next step is to put the model into practice, and to compare its predictions with actual field data. These are the topics covered in the last chapter of this thesis, Chapter 7.

Chapter 7

Virtual comparisons of autumn and spring calving systems using the IDFS model

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Abstract. The objective of this study was to illustrate the capability and potential applicability of the dynamic interactive dairy farm simulator (IDFS) described in detail in Chapter 6. Three sets of simulations in which 100% autumn- and 100% spring-calving systems were compared under different stocking rates (Comparison A), different climatic years (Comparison B), and with different quantities and qualities of herbage (Comparison C), are presented. The model predictions were compared with actual data from the field experiment presented in Chapter 2. All simulations were run using the same set of decision guidelines, based on the maintenance of a whole-farm average herbage mass (HM) at around 2000 kg DM/ha. Supplementary feed (defined in terms of energy and protein concentrations as maize silage) was fed to the cows when average HM was below target, and paddocks were "closed" for silage harvesting when average HM exceeded 2300 kg DM/ha. Post-grazing HM was set at 1700 and 1200 kg DM/ha for lactating and dry cows, respectively. Compared with actual data, the model predicted milksolids (MS) yields and lactation curves of autumn- and spring-calved cows with relative accuracy but it underestimated the amount of silage fed to the cows, and overestimated the amounts of silage harvested on each "farm". Increasing stocking rate (Comparison A) resulted in greater MS yields per ha, greater amounts of supplement fed, smaller quantities of silage harvested, greater amounts of herbage eaten per ha, and improved herbage utilisation. Compared with the spring calving system, the autumn calving system was less sensitive to the simulated effects of different climatic conditions (i.e. herbage accumulation rate, HAR) in terms of both MS yields and quantities of supplement fed (Comparison B). The differences in MS yields per cow between the two calving systems were smallest when HAR and herbage digestibility were increased during the summer period (Comparison C). In summary, the capability of the IDFS and its potential applications in terms of both the simulations of different scenarios and the generation of system hypotheses were demonstrated in the present study. The model simulates the key dairy farm components and their interactions with reasonable realism.

Keywords: simulation model; IDFS; calving season

1. Introduction

Using whole systems research to test hypotheses about the system is ideal, because the observations are made directly from the system in which either the researcher has a direct interest, or to which the research findings will eventually be applied. However, whole systems studies have three major constraints: they are very expensive, long-term, and are therefore physically limited to a relatively small number of treatments.

Mathematical modeling can be a complement of whole systems studies. Models can be used in this context either prior to field experimentation to evaluate different hypotheses and narrow the range of treatments to be applied, or during field experimentation to assist in decision making, or after field experimentation to verify the model structure or to validate the model with real data. Thus, the real advantage of mathematical modeling is that by bringing together knowledge about the system components, models can give "...a coherent view of the behaviour of the whole system.." (France *et al.* 1987).

A whole farm model, highly dynamic, interactive dairy farm simulator (IDFS) was developed and described in Chapter 6. In this chapter, predictions using IDFS are compared with actual data, and a set of 'virtual' comparisons between the autumn and spring calving systems is used to illustrate the capability, applicability, and limitations of the model.

2. Methods

Three sets of simulations were run using the IDFS model described in Chapter 6. In Comparison A, the effect of 2 seasons of calving (autumn and spring) and 5 levels of stocking rate (1.5, 2.0, 2.5, 3.0, and 3.5 cows/ha) were simulated. In Comparison B, autumn and spring calving systems, both stocked at 2.5 cows/ha, were simulated under 4 different climatic situations (normal, cold winter, dry spring, and dry summer), which were implemented by entering different historical HAR curves measured at No 1 Dairy farm in previous years as model inputs. Finally, Comparison C evaluated the effects of improved herbage production and herbage digestibility on the performance of autumn and spring calving systems stocked at either 2.5 or 3.0 cows/ha.

2.1. Decision rules used in the simulations

All simulations were run with the central aim of maintaining the average whole-farm herbage mass (HM) at, on average, 2000 kg DM/ha. This target was the same as the one used for the systems experiment described previously in this thesis (García *et al.* 2000, Chapter 2). In order to achieve this, the following decision rules were applied:

a) If HM decreased below target, supplements were fed to either the lactating cows, the dry cows, or both, in the amounts necessary to maintain the HM at its targeted level. The dynamic graphic displays that show the evolution of the average HM, average herbage accumulation rate, and average demand of herbage by the cows assisted the user for this purpose. Thus, supplements were not used to improve the diet of the cows but only to avoid the occurrence of feed deficits. In all simulations, "supplements" were defined as a 1:1 mixture of maize silage and grass silage.

b) If HM increased over 2300 kg DM/ha, the grazing area was reduced by 'closing' paddocks (up to 5 at one time) for silage harvesting. However, this decision rule was not applied if the increase in HM occurred in autumn and winter (as was the case in low stocking rates systems), as silage cannot be realistically made at these times of the year.

c) When closing paddocks up in spring (i.e. when HM reached the threshold of2300 kg DM/ha), the more recently grazed paddocks were selected. This is likely to occur in reality when herbage surpluses are identified earlier rather than later in the season.

d) The decision for harvesting the silage was based on the amount of herbage DM accumulated and on achieving the global target of 2000 kg DM after harvesting. In practice, for the main cut in middle spring, DM accumulated on the silage paddocks up to around 4000 kg DM[1], which is similar to what occurs in reality.

e) Dry cows were grazed on farm in all cases. Although in reality high-stocked dairy farms in NZ will usually graze some or all their dry cows off farm in order to save herbage for future use, from a modeling perspective this is the same as keeping these cows on farm and feeding supplements as required.

2.2. Variables maintained constant during the simulations

The following variables were maintained constant in all simulations:

[1] It should be remembered that the "ceiling yield" in the model was set arbitrarily to 4500 kg DM/ha (Chapter 6). This means that if undisturbed paddocks are allowed to achieve that maximum value, net accumulation rate in those paddocks will equal zero (i.e., senescence equals gross growth).

2.2.1. *Residual herbage masses*

Post-grazing (residual) HM (lactating cows) = 1700 kg DM/ha
Post-grazing (residual) HM (dry cows) = 1200 kg DM/ha
Residual HM after silage harvest = 1500 kg DM/ha

2.2.2. *Calving pattern*

In all cases, cows calved in a period of 10 weeks starting with the planned start of calving date (10 March for the autumn systems and 20 July for the spring system) according to the following calving pattern (% of cows calved per week for weeks 1 to 10): 29, 17, 13, 9, 9, 5, 5, 5, 3, 3. This pattern represents the average pattern of the actual calving systems comparison described in Chapter 2 (García *et al.* 2000).

2.2.3. *Lactation length*

In all simulations, the whole herd was dried-off when the group of cows that calved in the first week of the (previous) calving season achieved 305 days in milk. This resulted in an average lactation length of 285 days for all cases.

2.2.4. *Substitution rate*

Substitution rate (kg DM herbage not eaten/kg DM of supplement) = 1

In reality, because supplements were only used to cover periods of herbage deficit, it follows that supplements are expected to act in an 'additive' way, which would mean a substitution rate = 0. However, herbage in the IDFS model is consumed according to herd requirements and herbage availability, which means that decreasing the former (e.g. by feeding supplements) will slow down the rate of herbage consumption. An example will clarify this point. If there is 1 cow/ha with a potential intake at a given time of 15 kg DM/day with no supplements being fed, then the intake rate (or rate of herbage removal from the herbage pool) will equal 15 kg DM/day. If the cow is supplemented with 4 kg DM of silage, the model will act using the following logic:

If substitution rate = 1, then herbage intake = 11, and total intake = 15.
If substitution rate = 0.5, then herbage intake = 13, and total intake = 17.
If substitution rate = 0, then herbage intake =15, and total intake =19.

Under real farm conditions, the reduction of herbage intake from (using the same example) 15 kg to 11 kg would normally be achieved by restricting the cows' access to the pasture (i.e. by manipulating the time spent grazing on a particular paddock and the area grazed per day). In the IDFS model, this reduction is obtained by the amount of supplement fed and the substitution rate. Alternatively, herbage intake can be restricted by setting up the desired value in an input table, which overrides all other relationships in the model.

2.2.5. Quality of supplement

Supplements in IDFS are defined as one single feedstuff. This is because, from the model perspective, all what is important is the concentration of metabolizable energy (ME) and crude protein (CP) of the total supplement. For example in all the simulations carried out in Comparison A, the ME of the supplementary feed was 10.7 MJ/kg DM and the CP was 120 g/kg DM. These two values aimed to represent a common mixture (1:1) of maize silage (10.5 MJ ME and 70 g CP) and grass silage (11 MJ and 170 g CP).

2.2.6. Cows age, size and weight

All cows were 60 month old, had an average weight of 500 kg, and a standard reference weight (mature-size weight) of 580 kg.

2.2.7. Percentage of clover in the herbage

The proportion of clovers has a positive influence on DM intake (SCA, 1990; Chapter 6). For all simulations, the percentage of clover in the herbage was set at 20%.

2.3. Data analysis

Simulations were not replicated. Consequently, the three sets of whole-year simulations did not constitute actual experiments and are therefore regarded as "comparisons" rather than "experiments". The reason for doing this is simple. It is very easy to replicate treatments when using computer models, and it is even easier to obtain similar results between replications, provided (at least for the IDFS model) that the same decision rules were applied in all simulations. It follows that "statistical" differences between treatments are not difficult to obtain. The consequence of all these is that results "supported" by significant statistical tests may carry the risk of posing a greater emphasis in the numerical results *per se*, rather than in the evaluation of the model behaviour. More importantly, the interpretation of the main relationships and interactions among the key components of the system might be overlooked as a result of emphasising the numerical outputs of the model.

3. Results and Discussion

3.1. Comparison A

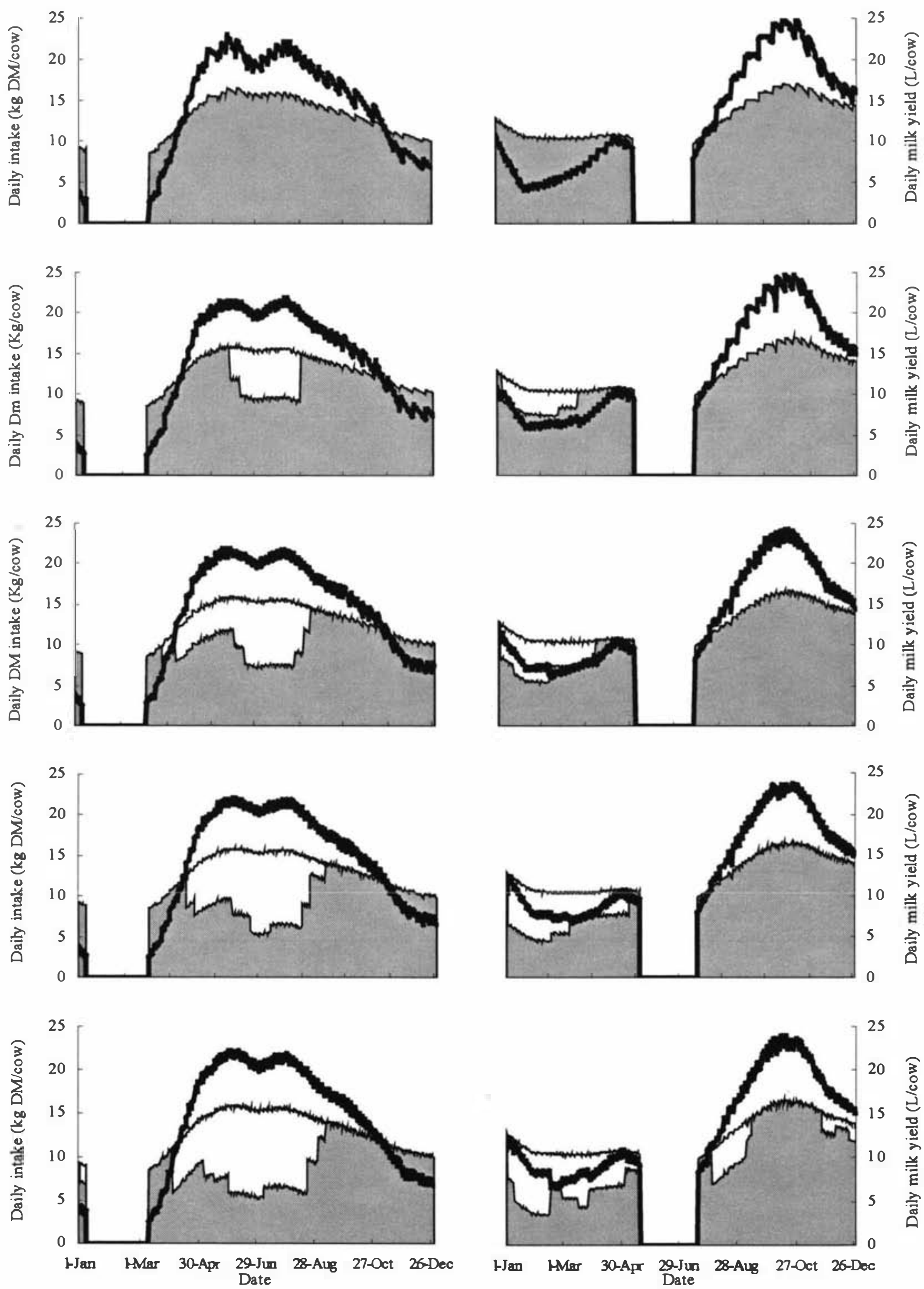
A summary of the results from Comparison A is shown in Table 1. As expected for both autumn and spring calving systems, higher stocking rates resulted in greater milksolids (MS) yields per ha, greater amounts of supplement fed, lower quantities of silage harvested, and greater amounts of herbage eaten per ha.

Table 1. Effects of stocking rate on the productivity of autumn and spring calving systems.

	Calving season									
	Autumn					Spring				
Planned Start of calving	10-Mar					20-Jul				
Stocking rate (cows/ha)	1.5	2.0	2.5	3.0	3.5	1.5	2.0	2.5	3.0	3.5
Milksolids production (kg)										
Total per cow	366	364	366	365	366	320	326	328	331	335
Total per ha	533	708	889	1064	1246	455	619	779	944	1115
Silage fed (t DM)										
Total per cow	0.00	0.41	0.81	1.11	1.36	0.00	0.21	0.38	0.68	1.00
Total per ha	0.00	0.81	2.25	3.76	5.25	0.00	0.42	0.95	2.03	3.58
% used for milking cows	0	100	87.8	78.5	79.2	0	100	100	82.3	84.1
Silage harvested (t DM/ha)	2.6	2.94	2.51	2.17	1.71	3.57	2.6	1.97	1.02	0.75
Herbage eaten (t DM/ha)										
Lactating cows	5.76	6.81	7.54	8.45	9.12	5.51	6.91	8.17	9.25	9.73
Dry cows	0.93	1.25	1.28	1.06	1.09	0.93	1.25	1.56	1.51	1.61
Total per ha	6.69	8.06	8.82	9.51	10.21	6.44	8.16	9.73	10.76	11.34
Total herbage 'harvested' (t DM/ha)	9.3	11.0	11.3	11.7	11.9	10.0	10.8	11.7	11.8	12.1

Milksolid yields per cow were not affected by stocking rate in the autumn calving systems. However, MS yields per cow increased with increasing stocking rates for the spring calving system. This effect was due to a higher total digestibility of the diet of cows during the summer when cows were supplemented with increasing levels of silage (higher stocked systems). At low stocking rates, the decision rules applied while running the simulations prevented the use of supplements during the summer. Therefore, milk yields were very low as a consequence of low herbage digestibility. With increasing stocking rates, the proportion of supplement in the diet also increased, resulting in greater quantities of total ME available for milk production for these spring-calved cows (Fig. 1).

Fig. 1. Simulation results for autumn (left column) and spring (right column) calving systems stocked at 1.5, 2, 2.5, 3, and 3.5 cows/ha (from top to bottom, respectively). Each graph shows milk yield per cow (black line), herbage DM intake per cow (filled area) and supplement DM intake per cow (non-filled area).



If only the silage harvested on farm had been available as supplementary feed, the results in Table 1 suggest that the adequate stocking rate (i.e. the stocking rate at which all the herbage harvested is consumed) would have been about 2.6 cows/ha for the autumn calving system, and about 2.8 cows/ha for the spring calving system.

Total herbage harvested by grazing and as silage (or net herbage grown, t DM/ha), increased from 9.3 (autumn calving system) and 10 (spring calving system) with the lowest stocking rate to about 12 t DM/ha when virtual farms were stocked at 3.5 cows/ha. Considering that the standard curve of HAR used as input was the same in all cases and had a total annual growth of 12.3 t DM/ha, the above values indicate an increase in herbage utilisation from 75% (autumn calving systems) and 81% (spring calving systems) at the lowest stocking rate, to 97-98% at the highest. The difference between either value and 100% (i.e., 12.3 t DM) represents a direct indication of the DM lost by senescence in each system (see Chapter 6). However, the observed curvilinear relationship between herbage utilisation and stocking rate for both calving systems (Fig. 2) indicates that marked improvements in herbage utilisation occurred when stocking rates were increased from 1.5 to 2.5 cows/ha, with little gain thereafter.

Fig. 2. Effects of stocking rate on herbage utilisation by autumn (■) or spring (▲) calving systems.

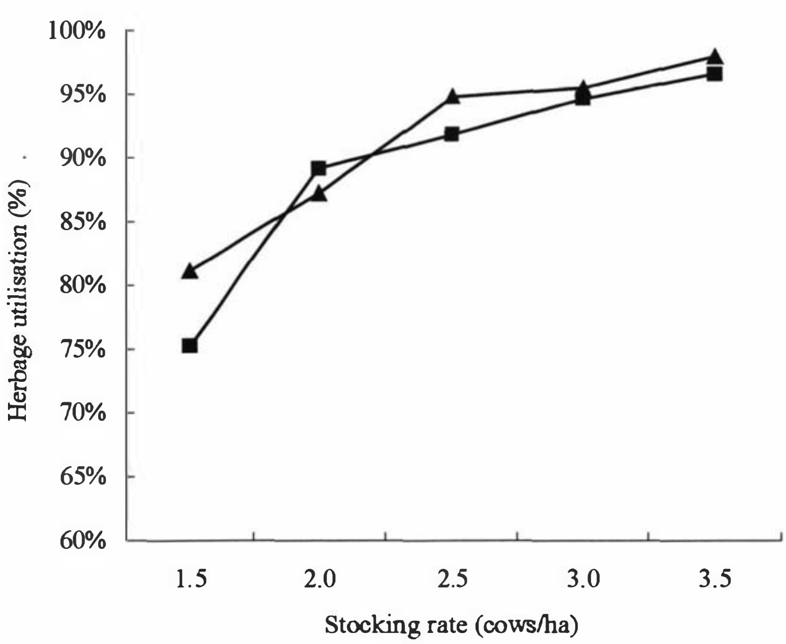
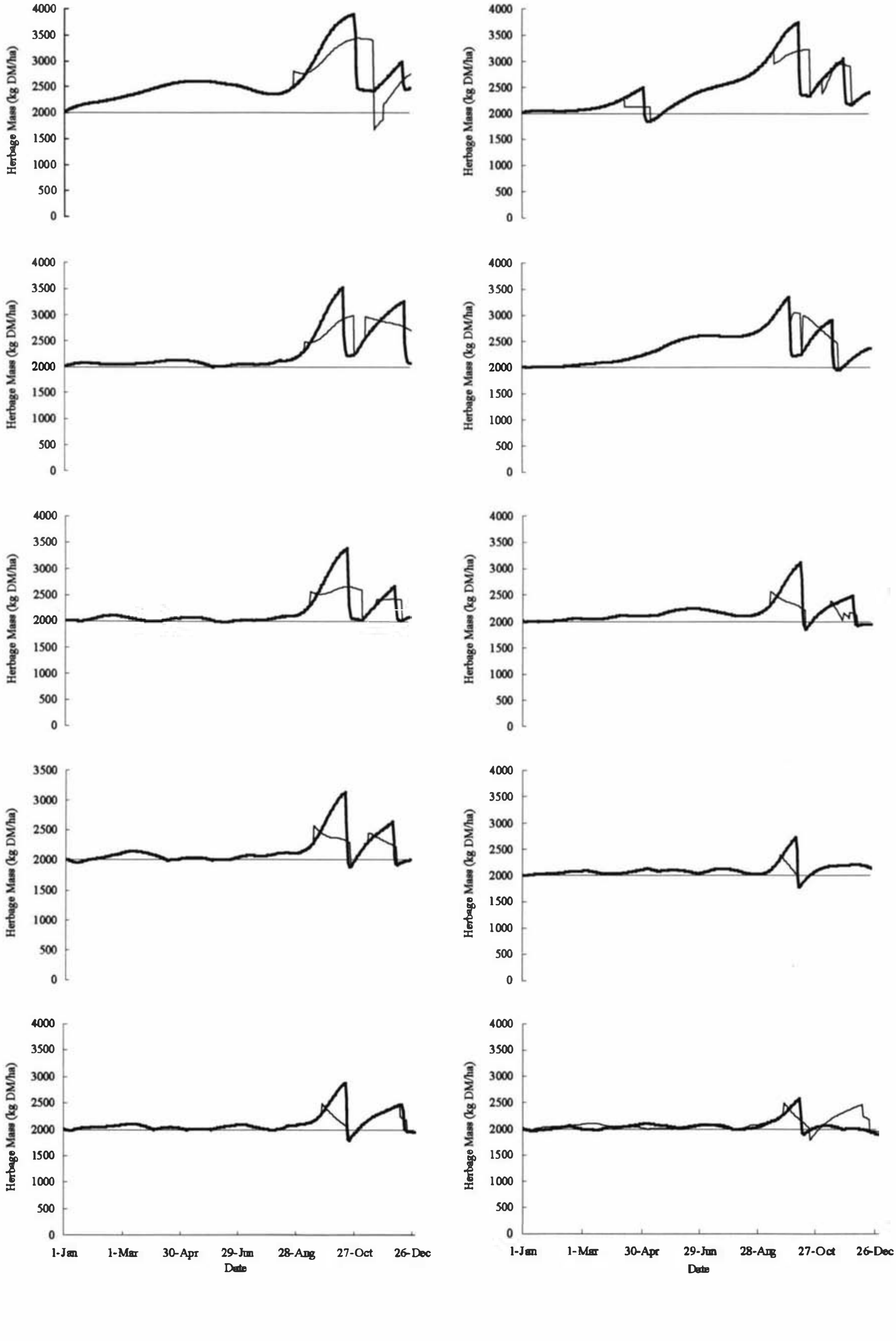


Fig. 3. Simulation results for autumn (left column) and spring (right column) calving systems stocked at 1.5, 2, 2.5, 3, and 3.5 cows/ha (from top to bottom, respectively). Each graph shows the average herbage mass in the whole farm area (thick solid curve), the average herbage mass in the grazing area (thin solid curve), and the target average herbage mass (straight line).



The smaller values of herbage grown/utilised at lower stocking rates resulted from the difficulties encountered to maintain the HM around the target value of 2000 kg DM/ha while simulating these systems (Fig. 3). This was because either the average HM increased over the threshold value of 2300 kg DM/ha (for closing up paddocks) at times of the year when silage making was not a realistic option (late autumn and winter), or because the reduction of up to 50% of the total farm area (maximum possible at any one time) was not sufficient to prevent further increases in the average HM. In the IDFS model, as herbage mass in any individual paddock approaches the ceiling yield (set arbitrarily at 4500 kg DM/ha, see Chapter 6), the senescence rate approaches the "gross" HAR, and the "net" HAR approaches zero, in accordance to the logistic equation incorporated in the model (equation 7, Chapter 6).

Table 2. Effects of different climatic conditions (i.e. herbage accumulation rate) on the productivity of autumn and spring calving systems stocked at 2.5 cows/ha.

	Calving season							
	Autumn				Spring			
Planned Start of calving	10-Mar				20-Jul			
Climate conditions	Normal	Dry spring	Cold winter	Dry summer	Normal	Dry spring	Cold winter	Dry summer
Total pasture grown (t DM/ha)	11.5	9.5	8.7	10.7	11.5	9.5	8.7	10.7
Milksolids production (kg)								
Total per cow	362	365	365	363	322	319	324	341
Total per ha	881	886	887	881	763	755	769	809
Silage fed (t DM)								
Total per cow	0.71	1.18	1.37	1.05	0.39	0.59	0.91	0.81
Total per ha	1.85	2.93	3.40	2.94	0.95	1.52	2.52	2.00
% used for milking cows	96	100	100	71.3	100	85	78.5	100
Silage harvested (t DM/ha)	1.8	1.1	1	1.9	1.54	0	0.5	1.43
Pasture eaten (t DM/ha)								
Lactating cows	7.73	6.56	6	7.39	8.16	7.8	7.1	7.1
Dry cows	1.48	1.56	1.56	0.71	1.56	1.34	1	1.56
Total per ha	9.21	8.12	7.56	8.1	9.72	9.14	8.1	8.66
Total pasture 'harvested' (t DM/ha)	11.0	9.2	8.6	10.0	11.3	9.1	8.6	10.1

3.2. Comparison B

The main results of Comparison B, in which equally stocked (2.5 cows/ha) autumn and spring calving systems were simulated under different "climatic" years (i.e. different total and seasonal patterns of HAR), are presented in Table 2. Once again the model predicted little variation for the MS yields of autumn-calved cows (and therefore per ha). Conversely, MS per ha for the spring calving systems ranged from 755 kg in the "dry spring' scenario, to 809 kg in the "dry summer". Thus, the application of the common set of decision rules resulted in greater quantities of silage being fed to the spring-calved cows during the dry summer, which in turn translated in greater total intakes of ME by these cows. Although the range of supplements fed to the autumn calving systems was also high (0.7 to 1.37 t DM/cow), the silage in this latter case was always fed during autumn and winter with little change in the total ME of the diet. Obviously using different concentrations of ME in the herbage, and/or the supplement, will change these results considerably (as shown below). The real advantage of the IDFS model is that any of these scenarios (as well as many others) can be easily set up and run, although the evaluations of all of them are beyond the objectives of this chapter.

3.3. Comparison C

In Comparison C the HAR actually measured in the 1992/1993 season (a good climatic year) was used as input in the model. In addition, herbage digestibilities were arbitrarily set at levels higher than normal, particularly during the summer with the aim of overcoming the restrictions suffered by the spring systems in the previous comparisons (low HAR and herbage digestibility during the summer).

Table 3. Simulation effects of improved quality and quantity of herbage (a "good" climatic year) on the productivity of autumn and spring calving systems stocked at either 2.5 or 3.0 cows/ha.

	Calving season			
	Autumn		Spring	
Planned Start of calving	10-Mar		20-Jul	
Stocking rate (cows/ha)	2.5	3.0	2.5	3.0
Milksolids production (kg)				
Total per cow	396	396	377	377
Total per ha	955	1146	899	1079
Silage fed (t DM)				
Total per cow	0.72	1.00	0.00	0.45
Total per ha	1.81	3.00	0.00	1.13
% used for milking cows	100	100	0	100
Silage harvested (t DM/ha)	2.93	2.00	1.32	0.56
Pasture eaten (t DM/ha)				
Lactating cows	7.92	8.6	9.59	10.33
Dry cows	1.56	1.87	1.56	1.87
Total per ha	9.48	10.47	11.15	12.2
Total pasture 'harvested' (t DM/ha)	12.4	12.5	12.5	12.8

The results presented in Table 3 show that again the model predicted greater yields per cow for the autumn- than for the spring-calved cows, at either 2.5 or 3.0 cows per ha. However, differences were smaller (5%) than those observed in Comparison A (range 9-14%) and in Comparison B (range 7-14%).

For the autumn-calved cows, an increment of 20% in the stocking rates translated into a similar 20% increase in MS yield/ha, but also in a 66% increase in the amounts of silage fed per ha (1.8 to 3.0 t DM). Similarly, in a "good" year the spring-calved cows did not require any supplementary feed at 2.5 cows/ha, but required 1.1 t silage DM per ha when stocked at 3 cows/ha. Considering the feed grown on-farm only, both systems were under-stocked at 2.5 cows/ha, but were over-stocked at 3 cows/ha. The fact that the deficit of supplement (total silage fed – total harvested) was smaller for the spring calving system suggests that the optimum stocking rate (somewhere between 2.5 and 3.0 cows/ha) would be slightly higher for these cows than for the autumn-calved cows, which is in agreement with the results obtained in Comparison A. This suggests that if both systems were stocked at their optimum stocking rate (defined here in terms of utilising only grazing herbage and silage harvested on farm), the spring calving systems could compensate their lower yields per cow with higher stocking rates, which might in turn result in similar yields per ha.

3.4. Comparison of predicted and actual data

The comparison between the actual average values for 100% autumn and 100% spring systems (García *et al.* 2000, Chapter 2) and those predicted by the model at the same stocking rates are shown in Table 4. Milksolids yields in Table 4 are expressed as total farm MS divided by the nominal number of cows (as in Chapter 2). This is different from Table 1 in which MS yields were expressed as the 'actual' (weighted) average yield per cow and per ha.

Table 4. Comparison of actual (García *et al.* 2000, Chapter 2) and predicted (IDFS model) results.

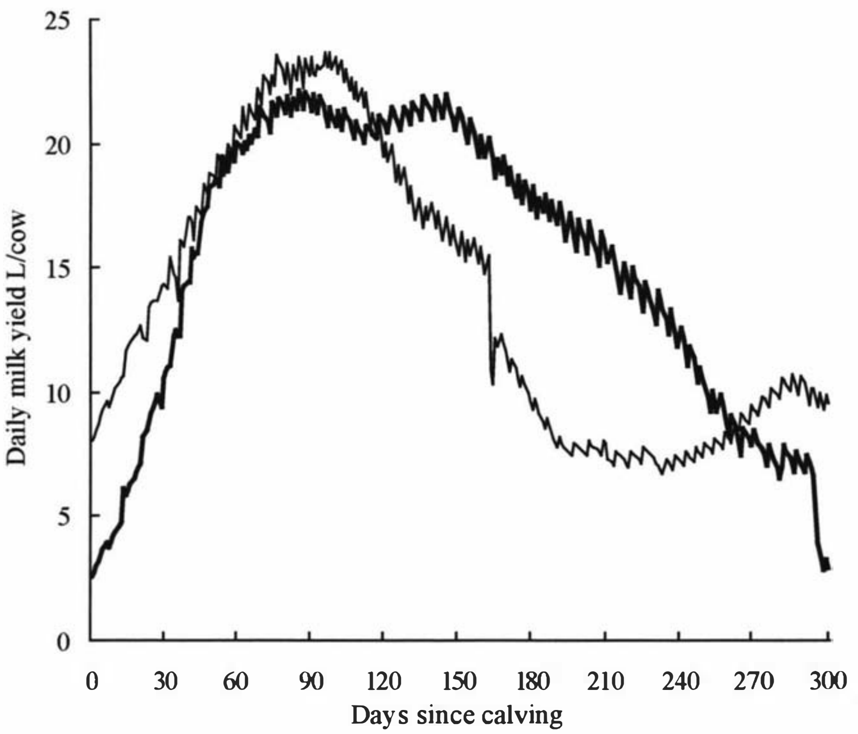
	Calving system					
	100A			100S		
	P	A	P/A	P	A	P/A
Nominal stocking rate (cows/ha)	2.0	2.0	-	2.5	2.5	-
Milksolids yields (kg)						
Per cow	354	361	0.98	312	309	1.01
Per ha	708	723	0.98	779	750	1.04
Supplements fed (t DM/ha)	0.8	2.3	0.35	1.0	1.7	0.57
Supplements harvested (t DM/ha)	2.9	2.4	1.21	2.0	1.0	1.97

100A = 100% autumn calving system; 100S = 100% spring calving system; P = values predicted by IDFS model; A = actual values from the calving systems comparison (Chapter 2).

Predicted MS yields per cow and per ha were both within 4% of actual values. However, the model significantly underestimated (by 43% to 65%) the quantities of silage fed to the cows, and overestimated (by 21% to 97%) the quantities of silage harvested.

It is important to note that the model considers no inefficiencies due to grazing or feeding supplements. That is, if total daily demand of herbage DM is for instance 30 kg, then exactly 30 kg will be "removed" from the herbage pool. Further, in the real farm situation supplements "fed" actually means supplements "offered" to the cows, but it means DM actually "consumed" by the cows in the IDFS model. If both herbage DM disappearance (other than by grazing) and silage wastage were considered (with common values of about 10% and 20-25%, respectively; see Chapter 5), then predicted and actual values of supplements fed and harvested would be in better agreement.

Fig. 4. Simulated lactation curves of autumn- (thick line) and spring- (thin line) calved cows.



The shape of the lactation curves of autumn-calved cows differed markedly from those of the spring-calved cows in the actual whole systems comparison, a topic presented in Chapter 2 (García *et al.* 2000) and discussed in detail in Chapter 3 (García and Holmes, 2000). Similar differences were also observed for the lactation curves predicted by the IDFS model between autumn and spring calving cows. Thus, compared with autumn-calved cows, cows calved in the spring had a higher peak of lactation (23-24 v 21-22 l/cow.day), but a lower persistency (greater drop) after the peak (Fig. 4). Conversely, autumn-calved cows had a flatter curve with a small drop between days 90 and 120 post-calving, which resulted in two distinguishable peaks. The decrease in milk yield during winter was a result of lower values of herbage digestibility measured in July in the system comparison. Obviously this drop could be overcome in the model by increasing the digestibility values of the herbage, the supplement, or both, as is demonstrated in Comparison C.

Of more importance, however, is the indication that the greater MS yields per cow by the autumn-calved cows, which were observed in all three comparisons, were due to greater yields in mid and late lactation by these cows. These differences were not due to lactation lengths, which were the same (average 285 days) for all systems. This agrees with the results from the field experiment (García *et al.* 2000; Chapter 2), in which autumn-cows outperformed their spring-calved counterparts due mainly to greater yields in mid and late lactation rather than to longer lactations (García and Holmes, 2000; Chapter 3).

4. Final remarks

The above speculation with regards to the optimum stocking rate of systems with contrasting calving dates illustrates how IDFS can assist the researcher in developing new system hypotheses. Furthermore, the selected hypotheses can easily be tested as shown for Comparisons 1, 2, and 3.

Model predictions were in relatively good agreement with actual field data for both the total yields (per cow and per ha) and the shape of lactation curves of autumn- and spring-calved cows. This suggests (but does not prove) that the model predicts the main relationships and interactions that occur in real systems with reasonable realism. However, quantities of silage fed to the cows and harvested were under- and overestimated, respectively, and the reasons for this are not obvious, although they could be due partly to DM losses which were not included in the model.

The dynamism of the model can be appreciated in the sequences of simulation results shown in Fig. 1. Herbage accessibility and herbage digestibility both affect total herbage DM intake by the cows (Chapter 6). Thus, as HM decreases while cows are grazing a paddock, so does the relative availability of herbage, and consequently relative and actual intakes decreased too. It follows that systems with lower stocking rates, which will almost inevitably maintain higher levels of pre-grazing HM, will show also more marked ranges between initial and final intakes values (and therefore milk yields), or a "saw-shaped" effect (Fig. 1).

In summary, this chapter showed the capabilities of the IDFS and its potential applications in terms of both the simulations of different scenarios and the generation of new system hypotheses. The model simulates the key dairy farm components and their interactions with reasonable realism.

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General Discussion

1. Introduction

This thesis has integrated system, analytical, and modelling approaches in order to study some of the factors, relationships, interactions, and physical outputs of pasture-based dairy systems which differed in their calving date. The results of each of the studies have been presented in the respective chapters, each of which included specific discussions of the topic being covered.

This general discussion is not intended to repeat previous discussion sections. It is intended, however, to highlight and integrate the main outcomes of each of the approaches, and to discuss them from a broader perspective.

2. Systems study

A central objective of the present study was to investigate the physical performances of pasture-based dairy systems that differed in their calving dates. Spring calving systems are considered to synchronise herd requirements and pasture growth better. However, the literature reviewed in Chapter 1 identified sufficient evidence to suggest that autumn calving systems could have performances similar to those obtained from spring calving systems, provided that a minimum amount of supplementary feed was available. Chapter 1 also highlighted the need for systems research to test these effects, because such a large number of factors, relationships and interactions were involved. Therefore, the hypothesis that systems with contrasting calving dates could achieve similar performances was tested in a 3-year study conducted at No 1 Dairy Farm, Massey University, and results presented in Chapter 2 offered no evidence to reject it. Key contributors to this conclusion were the facts that all systems utilised (on average) similar amounts of supplements per ha, and that autumn-calved cows had greater yields of milksolids per lactation despite lower daily yields at peak of lactation than spring-calving cows (Chapter 3). The greater total yields per cow by the autumn-calved cows resulted from greater daily yields in mid and late lactation in conjunction with longer lactations by these cows (Chapter 3). Differences in stocking rate between the two 100% calving systems had little influence on this effect, because the autumn-calved cows had greater yields than the spring-calved cows even within the 50/50 system, in which both autumn- and spring- calved cows were stocked at the same rate (Chapter 3). An important practical implication of these findings is that, when the whole system is considered, higher daily yields at peak of lactation are not necessarily synonymous with greater total lactation yields, as may be the case for other types of production systems.

The similar physical performances achieved by systems with contrasting calving dates (Chapter 2) might have important implications at the whole industry level and also at a level comprising more theoretical aspects of pastoral farming. From the broader perspective of the dairy industry, the present results suggest that factories could benefit from a more even distribution of autumn and spring (or autumn/spring) calving systems. That is, if a significant proportion of cows were calved in the autumn, the factories could have the double benefit of increasing the utilisation of the installed physical facilities by processing more milk during winter, while at the same time removing pressure from the spring "flush". In addition, milk produced in late lactation by the autumn-calved cows had lower concentrations of somatic cells than milk from the spring-calved cows at the same stage of lactation (Chapter 3), which may have important implications for milk processing. Finally, greater yields by the autumn-calved cows could translate into similar total yields being achieved by a relatively smaller number of cows in autumn-calving systems.

From a more theoretical point of view, it is interesting to note that the philosophy behind the development of the New Zealand dairy system has been built during the past century around the concept of synchronising the changing rates of cows' requirements with the changing rates of herbage accumulation. In other words, concentrating the calving season in late winter-early spring should result in the highest efficiency in terms of herbage utilisation and whole-system performance. It is actually accepted that this is the main reason that explains the higher physical performance per ha (relative to international standards) achieved by New Zealand dairy farms. However, the results of this thesis do not support this view. That is, provided a minimum amount of supplements were available (about 20% of total requirements for the systems compared here), then autumn calving systems can achieve similar overall efficiencies to those achieved by spring calving systems. The reasons for this were twofold. First, despite the fact that the majority of the herbage growth occured during the spring season (Chapter 5), this herbage was converted to milk in both systems. Further, the greater yields in mid and late lactation by the autumn-calved cows were a direct consequence of the spring growth of herbage (Chapter 2 and Chapter 3), which resulted in greater feed conversion efficiencies in mid lactation by autumn-calved cows than spring-calved cows (Chapter 5). This result has been shown in this thesis not only by the results from the field experiment (Chapter 2, 3, and 5) but also by the predictions of a whole-farm model that was developed totally independently of the field data (Chapter 6 and 7). It cannot be overstated, however, that both real and virtual systems compared in this thesis were not 'closed' or 'self-contained' units. Had they been self-contained units, then results could have been totally different as reported by Fulkerson et al. (1987) (see Chapter 1).

3. Dry matter intake

A second goal of the present study was the development of more appropriate methodologies for investigating some of the central processes and interactions that govern the systems' behaviour, of which the amounts of DM consumed by the cows was identified as a key factor. Intakes of herbage DM by grazing animals are very difficult to measure, particularly in a whole-system study. The commonest, and probably the simplest, methodology is the estimation of herbage DM intake by the difference method, which involves measurements of HM present before and after each grazing. This methodology was used during a major part of the field experiment (Chapter 5). However, the difference method does not provide any information of DM intakes by individual animals, thus restricting the potential usability of the data.

Marker-based methods constitute widely accepted techniques for estimating DM intakes by individual, grazing animals. In particular, the n-alkanes method is becoming commonly used in many field studies involving grazing dairy cows (Dove and Mayes, 1991). However, this method alone may be of little help for whole systems studies in which the grazing cows are being supplemented with silage as a group (either on feed pads or on the ground in the paddock). In this thesis a methodology that combine the n-alkanes method and the ^{13}C method has been developed and validated (Chapter 4), and used in an additional study (Chapter 5). To the author's knowledge, this methodology constitutes the only available technique that enables, at the same time and without adding any additional work to the n-alkanes technique, the estimation of DM intakes of herbage and maize silage by individual grazing cows which are being given access to the silage as a group. The advantages of the technique are its relative simplicity and lower cost, minimum disturbance of the cows, and the high precision of the ^{13}C analysis. The method, however, has several disadvantages. First, the method does not allow different plant species within a photosynthetic pathway to be distinguished (e.g. it could not distinguish between silage made from ryegrass and grazed ryegrass). Second, digestibility coefficients for both the grazed herbage and the maize silage must be known. Third, because it is based on carbon proportions in the faeces, drastic modifications of the amounts of silage and herbage eaten by the cows might lead to errors in the estimated intakes (Chapter 4).

The method was used with an independent set of data and proved useful (Chapter 5). However, it should be remembered that even though the method was validated indoors (i.e. compared to weighed intakes, see Chapter 4), this is not definitive proof that it will perform identically under grazing conditions. Complete validation of any method under grazing conditions is, unfortunately, impossible.

The possibility of further investigating the variation (and causes) in DM intakes of maize silage and herbage by undisturbed, grazing, individual cows constitutes the greatest applicability of the method. The fact that cows differ in their total daily intakes of DM is well known by researchers and by dairy farmers, but the magnitudes of the difference are not known. The methodology developed in this thesis allows these differences to be quantified, as shown in Fig. 3 (Chapter 4) and Fig. 7 (Chapter 5) for two different short-term studies. Only a few cows in each study had intake levels of maize silage close to the group-average, and coefficient of variation between cows ranged between 30% and 49%.

In both studies total DM intake was positively related to milk yield by individual cows. However, in the first study, differences in maize silage intake were unrelated to differences in milk yield, because higher yielding cows compensated for their greater requirements by consuming more herbage DM (Chapter 4), while in the second study the higher yielding cows consumed more maize silage DM (Chapter 5). This apparent contradiction between the studies was attributed to differences between experiments in terms of herbage allowance, and in the way the silage was offered to the cows (in troughs or on the ground in the paddocks). Nevertheless, the combined data from both studies suggest that grazing dairy cows supplemented with maize silage will compensate for their different individual feed requirements by increasing the DM intake of either herbage or maize silage, whichever is less restricted or accessible. As noted in Chapter 5, a practical application of this could be a greater focus on the importance of improved accessibility to the supplementary feed, in terms of either feeding time or feeding space.

From a broader perspective, however, the relatively large variation in DM intakes among individual cows raises a question about the extent to which the common management in New Zealand, which is generally based on feeding the "herd" rather than the individual cows, might be limiting production of individuals in the herd. Clearly, this is an area that requires further research.

4. Modelling

The integration of field systems research with modelling analysis is crucial. For example, results in Chapter 2 have shown that systems with contrasting calving dates had similar overall efficiencies in terms of physical performance and inputs. However, what would have happened if the cows in both 100% calving systems had been stocked at the same rate? Or what would have happened if the systems had been managed using decision rules different from those actually used (Chapter 5)? Or if the supplements used had been of better quality? Or if...

Clearly, the number of questions and hypotheses are infinite. Clearly also, only a few of them could be feasibly answered by means of field-based experimentation, due to limited resources.

The third objective of this thesis was to integrate methodologies by means of modelling analysis. Whole farm models such as UDDER (Larcombe, 1989) can be used to answer some of the above questions and/or to test the hypotheses derived from those questions. However, these models do not allow the user to interact with the model and to make decisions during the simulation, and therefore, they do not resemble the continuous process of decision making that occurs in reality. In contrast, the model developed as part of the present thesis (Chapter 6) allows (and actually "needs") the operator to make decisions during the simulation. Therefore, it allows all the above questions, and many others, to be addressed.

The model can simulate seasonal pasture-based dairy farms with reasonable realism, as was shown by the comparison of actual and predicted data in Chapter 7. However, the model is at a relatively early stage of development, and cannot be considered as a "validated" model.

Validation of whole-farm models is not a trivial task. Validation involves ensuring that the model is adequate for its intended use, although it is a process usually restricted to a comparison of actual and predicted data (Harrison, 1990; Qureshi *et al.* 1999). However, the first question to be answered is: should the final (or more important) outcomes of the model (such as milk yields) be compared with actual data? Or should the validation focus on the internal relationships (equations, interactions) of the model? The process of ensuring that these internal relationships behave correctly is known as *verification*. However, the fact that an internal equation (or a set of equations) behaves as intended does not necessarily imply that that particular equation (or relationship) is validated. For example, in IDFS net herbage mass accumulation rate in any paddock decreases when the average herbage mass increases up to a limit (= 4500 kg DM/ha), at which the net growth is zero. It can be easily *verified* that this relationship behaves as intended. In fact, it is well known that undisturbed pasture will achieve a "ceiling yield" (or net growth = 0) eventually (Lemaire and Chapman, 1996). However, it is still not known whether this equation represents the real world correctly (i.e. quantitatively). In other words, this particular equation (given as an example here) cannot be considered to be validated.

Clearly, with relatively big and complex models, some of sort of "buffering" or compensation may occur as a result of the many interactions and cross-references between all the factors involved. If this is the case, an incorrect internal relationship of the model can easily be overlooked.

Nevertheless, the IDFS model was developed with the aim of providing an innovative tool for the study of pasture-based dairy systems, which would allow the researcher to set up and run experiments, based on previously defined decision rules. In this sense, and despite the fact that a formal validation is still needed, the results in Chapters 6 and Chapter 7 show that the model is useful for the purpose it was intended.

5. Future use of IDFS

Once additional tests of the model's validity are performed, the IDFS can serve multiple purposes. First, it could assist the researcher's interest in studying the behaviour of pasture-based dairy systems. This assistance could take the form of ~~a~~ "screening" a range of possible systems prior to field experimentation, or analysing the effects of different sets of decision rules for field experimentation, but prior to making the real decisions.

Secondly, it could be used for teaching and/or training purposes. One of the model's major advantages comes from the dynamic and visual nature of its outputs, which enable the users to see, clearly and immediately, the consequences of their own decision making.

Finally, from a more practical perspective, the IDFS could assist dairy farm managers in some of their managerial decisions. For example, successful managers must routinely estimate the total feed demand (herds' requirements) and the total feed supply (herbage growth). Of course, in this example the problem lies in the unknown nature of the latter. With IDFS, different scenarios simulating different herbage growing conditions could be set up easily, and the manager could graphically observe the consequences of the intended short-term decisions on the performance of cows, the use of supplements, the pre- and post-grazing herbage masses, etc. An advantage of the model for this purpose is that the initial and final time of the simulation (and therefore its duration) can be specified from hours to years, starting at any desired time in the calendar year.

6. Conclusions

This thesis has demonstrated that dairy systems which had very contrasting calving dates can achieve similar physical performances and overall efficiencies, and that, contrary to previous belief, cows calved in the autumn can outperform their spring-calved counterparts. A key determinant in this effect was the differences in the lactation curve of autumn- and spring-calved cows, and the strong response of mid-lactation cows (autumn-calved) to the improved availability of high quality pasture in the spring season.

Studies of whole-farm systems constitute an invaluable tool for comparison of systems. However, this thesis has shown that much greater benefits can be obtained by means of a 'multi-approach' project in which systems studies are combined with component research and modelling analysis. Two new tools have been developed in the present thesis. Within the component research approach, a methodology was developed to estimate the intakes of herbage and maize silage DM by individual grazing cows under undisturbed, real-life conditions. Within the modelling research approach, a new whole farm, dynamic and interactive model has been developed. It is the author's hope that, in the future, this model could assist researchers to investigate system hypotheses, decision rules, and the factors and interactions of the main system components; students to be the protagonists of their own learning process; and farm managers to better evaluate their managerial decisions.

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Errata

Page	Location (Line, paragraph, table, graph)	Where it says...	It should say...
vii	3rd paragraph	"the thesis into chapters..."	"the papers into chapters..."
43	Line 5	"responsible of..."	"responsible for..."
114	Line 7	"is not known,..."	"are not known,..."
127	Table 5 (last 2 footnotes were omitted)		[8]Predicted using ME demands for maintenance, actual milk production, and LW changes [assuming 0.6MJ/kg $LW^{0.75}$, 4.8 MJ ME/litre of milk, 38.5 MJ ME/kg LW gained, and 32 MJ ME/kg LW lost (Holmes *et al.* (1987)] [9]FCE = feed conversion efficiency (g MS/kg DM eaten)
149	Abstract, 2nd line from bottom	"at present stage..."	"at its present stage..."
166	Final remarks, 1st line	"at present stage..."	"at its present stage..."
166	2nd line from bottom	"dairly..."	"dairy..."
180	3rd line	"risk of posing..."	"risk of placing..."
180, 184, 185	Table 1 Table 2 Table 3 (footnote omitted)		Milksolids are accumulated yields during the simulation. Therefore, total milksolids per ha will not equal total per cow x stocking rate because not all cows started to produce milk on the same day.