CSIRO PUBLISHING
Animal Production Science, 2010, **50**, 246–264 www.publish.csiro.au/journals/an

Development of profitable milk production systems for northern Australia: a field assessment of the productivity of five potential farming systems using farmlets

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Abstract. Farmlets, each of 20 cows, were established to field test five milk production systems and provide a learning platform for farmers and researchers in a subtropical environment. The systems were developed through desktop modelling and industry consultation in response to the need for substantial increases in farm milk production following deregulation of the industry. Four of the systems were based on grazing and the continued use of existing farmland resource bases, whereas the fifth comprised a feedlot and associated forage base developed as a greenfield site.

The field evaluation was conducted over 4 years under more adverse environmental conditions than anticipated with below average rainfall and restrictions on irrigation. For the grazed systems, mean annual milk yield per cow ranged from 6330 kg/year (1.9 cows/ha) for a herd based on rain-grown tropical pastures to 7617 kg/year (3.0 cows/ha) where animals were based on temperate and tropical irrigated forages. For the feedlot herd, production of 9460 kg/cow.year (4.3 cows/ha of forage base) was achieved. For all herds, the level of production achieved required annual inputs of concentrates of ~3 t DM/animal and purchased conserved fodder from 0.3 to 1.5 t DM/animal. This level of supplementary feeding made a major contribution to total farm nutrient inputs, contributing 50% or more of the nitrogen, phosphorus and potassium entering the farming system, and presents challenges to the management of manure and urine that results from the higher stocking rates enabled.

Mean annual milk production for the five systems ranged from 88 to 105% of that predicted by the desktop modelling. This level of agreement for the grazed systems was achieved with minimal overall change in predicted feed inputs; however, the feedlot system required a substantial increase in inputs over those predicted. Reproductive performance for all systems was poorer than anticipated, particularly over the summer mating period.

We conclude that the desktop model, developed as a rapid response to assist farmers modify their current farming systems, provided a reasonable prediction of inputs required and milk production. Further model development would need to consider more closely climate variability, the limitations summer temperatures place on reproductive success and the feed requirements of feedlot herds.

Additional keywords: dairy farming, nutrient balances, subtropics.

Introduction

The subtropical dairy industry in Australia, located between the latitudes of 17 and 32°S, produces 10% of the nation's milk and comprises mainly family farms with a typical herd size of 150 cows (Hetherington *et al*. 2000). The feedbase comprises improved pastures and sown forage crops supplemented with grain, industry by-products and conserved forage. Until the year 2000 the State regulated milk prices and farmers received a large price differential between quota (fresh milk) and the above quota milk (manufactured milk).

Deregulation of the milk marketing chain resulted in the introduction of a single and lower overall milk price. While the average price fell from ~A$0.40/L to A$0.32/L (Bake *et al*. 2002) farmers had more flexibility to vary production throughout the year. The challenge was how to respond to this new lower price coupled with greater production flexibility. Analyses of production systems showed only modest potential to reduce costs (Hoekema *et al*. 2000); however, past analyses had shown a generally high potential for increased milk output (Kerr *et al*. 2000) as cows and infrastructure are often used well below their potential.

Callow *et al*. (2005) used a modelling approach to identify five production systems that had the economic capacity to provide a way forward for farming families in the new deregulated environment. Four of these systems maintained a grazed forage base and had the potential to increase milk output substantially without having to expand the farmland resource base, while the fifth, a feedlot, was more suited to a greenfield site in a low rainfall environment (<600 mm/year). Features common to the four grazed systems were large increases in both milking cow numbers and in the level of feeding of purchased supplementary feed (Callow *et al*. 2005). Such rapid intensification had implications for farming families across matters as diverse as herd, financial, labour and environmental management. As there

 10.1071/AN09124 1836-0939/10/040246

were no existing case studies of such rapid development from which to learn, there was a need to field test the proposed farming systems. Such an assessment needed to include production and profitability goals, and also environmental and sociological robustness. To assist this assessment, physical models (farmlets) of the five proposed farming systems were established on the Queensland Government's Mutdapilly Research Station. The purpose of the farmlets were to compare production with model predictions (Callow *et al.* 2005), provide a platform for biophysical investigations and extension activities, and complement other activities conducted on commercial farms (Andrews *et al.* 2003).

Farmlets, small herds used to represent a whole farm system and usually located on a research station (Crawford *et al.* 2007), have traditionally been used in experimental studies in Australia and New Zealand to develop response functions to one or more factors such as fertiliser rate, stocking rate, genetic merit or supplementary feeding levels (Thomas and Matthews 1991; Fulkerson *et al.* 2008; Valentine *et al.* 2009). In the current study, farmlets were used differently in that each farmlet was developed as a stand-alone enterprise based on model outputs, with its own specific goals and decision rules (Anon. 2001; Andrews *et al.* 2003). The farmlets were also part of an active extension program providing an interactive learning platform for farmers, researchers and advisers (Paine *et al.* 2002). This paper focuses on three aspects of the farmlet study; the relationship between actual and predicted production on an annual (Callow *et al.* 2005) and weekly basis, the productivity of each farmlet and, as an indicator of potential environmental risk, whole farmlet nutrient efficiencies and surpluses (Gourley *et al.* 2007).

Materials and methods

Site description

Mutdapilly Research Station is located in a subtropical environment in south-eastern Queensland (27°45′S, 152°40′E; alt. 40 m) with a summer-dominant rainfall pattern. Long-term mean annual rainfall is 800 mm (s.d. 205), with 70% falling from October to March inclusive, and mean annual pan evaporation is 1825 mm (Clewett *et al.* 2003). Rainfall during the 4 years of this study was below the long-term average in all years at 651, 648, 751 and 667 mm/year with the autumn–winter period particularly affected (Fig. 1). In contrast to other years, winter rainfall in Year 2 provided generally favourable cool season growing conditions while flooding rains and elevated temperatures were a feature of summer 2003–04 (Year 3). Summers are hot and humid while frosts are common in June and July. Over the study period, maximum temperatures tended to be higher than average (Fig. 1). Relative humidity during January and July at 9:00 a.m. and 3:00 p.m. (EST) was 70 and 51%, and 68 and 43% respectively.

A self-mulching cracking clay, located on alluvial flats (Grey/Black Vertosol) was the major soil used for forage production. This soil is neutral on the surface and strongly alkaline at depth with a clay content of 60–75% in the surface soil (0–10 cm) rising to 68–84% deeper down the profile (50–60 cm). The estimated rooting depth is 0.9 m with a plant available water holding capacity of around 130 mm (Powell *et al.* 1985). The feedlot facility (M5) and dairy were located on the low hills on a medium clay soil (Brown Vertosol). Soon after the project commenced, due to a sequence of lower than average

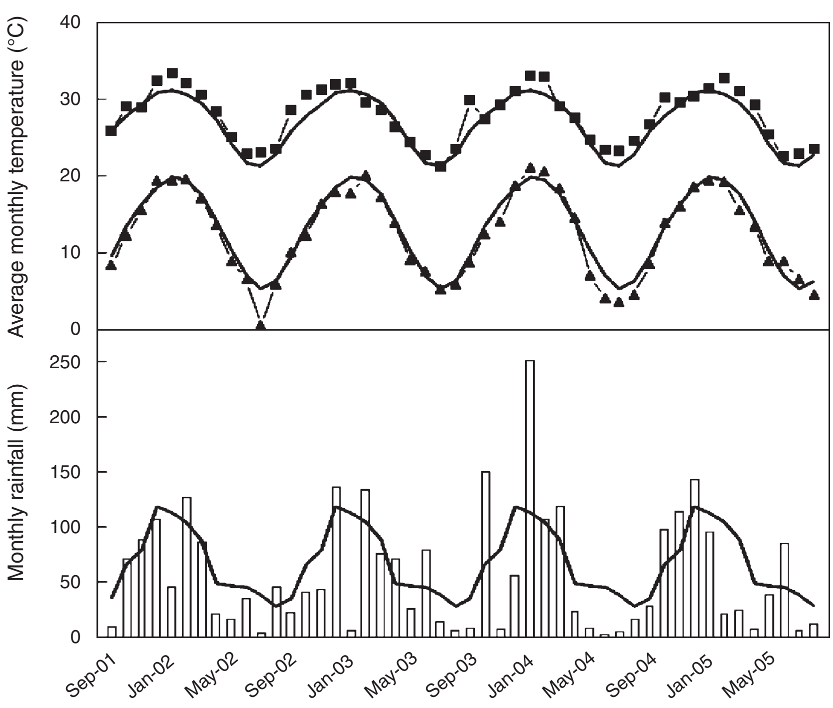

Fig. 1. Mean monthly district maximum (■) and minimum (▲) daily temperatures vs long-term average (solid line) and Mutdapilly monthly rainfall (open bars) vs long-term district average (solid line) between September 2001 and August 2005.

rainfall years (Clewett *et al*. 2003), supply from the local irrigation scheme was terminated and groundwater bores were relied on to supply all irrigation requirements. This resulted in a progressive reduction in supply to farmlets from 90% of allocation in Year 1 to 50% in Years 3 and 4. All irrigation water was supplied by overhead spray using high pressure gun irrigators.

Farmlet description

The 20-cow farmlets were established using the parameters developed for each farming system in the desktop study (Callow *et al*. 2005) with inputs (fertiliser, supplementary feed, irrigation) and land area allocated on the basis of the proportional difference between farmlet and system herd size (Table 1). The pasture/crop area for each farmlet comprised two to five different forage bases (Table 2). Due to climatic conditions that prevailed over the study period, there was some difference in actual supplementary feeding and irrigation levels from that predicted (Table 5).

Milk harvesting, shade, watering and feedlot

Farmlets used a common dairy. M1 to M4 herds were provided with water in all paddocks and a limited area of shade (3 m^2/animal) provided by mobile shelters. The M5 herd was confined to an area of land comprising a concreted and covered feed pad (80 m^2) and associated gravel-based loafing area (800 m^2). Additional cooling, through automated overhead sprinklers, was implemented for this herd in the final summer (Year 4) of the study. The concrete feed pad was dry scraped daily.

Allocation to herds

Holstein-Friesian cows from the Mutdapilly herd were allocated to the farmlets on the basis of previous milk production, calving date and age (Table 3). For the grazing farmlets, M1 to M4, animals were randomly allocated following blocking. For the feedlot herd (M5), there was a deliberate selection bias towards animals from the top half of the herd, based on Australian Breeding Values, to mimic that expected in the development of a greenfield enterprise of this nature.

Farmlet management

Herd reproductive management and replacements

All animals were mated using artificial insemination within a batch calving (M1 to M4) or year-round (M5) program. Batch calving involved two seasons (spring and autumn) with the spring calving contributing 100, 50, 30 and 35% of all calvings for M1 to M4 respectively. For M5, year-round calving was planned with the objective being to calve 25% of cows in each quarter. To achieve a spring calving, mating had to take place over the summer months. For M1, mating commenced on December 1 or at 6 weeks after calving and continued until early March, while for M2 to M4 mating continued to the end of February. For autumn calving, mating commenced May 1 or 6 weeks after calving and continued to the end of August. From Year 2 onwards,

Table 1. Physical features of the five farmlets at Mutdapilly Research Station

Parameter	Farming system				
	M1 (raingrown, pasture)	M2 (limited irrigation, pasture)	M3 (limited irrigation, crop)	M4 (irrigation, high quality pasture)	M5 (irrigation, feedlot)
Pasture/crop area (ha)	10.7	7.35	14.40	6.70	4.65
Irrigation					
Irrigable area (ha)	Nil	1.5	1.6	6.1	4.7
ML/ha.year	Nil	4.6	3.9	4.3	4.1
Purchased feed					
Hay/silage (t DM/cow.year)	1.2	0.9	0.4	0.3	1.5
Concentrate mix (t DM/cow.year)	2.7	2.9	2.8	2.8	3.2
Stocking rate (head/ha)	1.9	2.7	1.4	3.0	4.3

Table 2. Area (ha) of pasture and crop type allocated to each farmlet herd

Feedbase	M1	M2	M3	M4	M5
Improved tropical grass (raingrown)	8.32	5.85	1.85	0.60	0
Winter cereal forage crop (raingrown)	2.38	0	6.00	0	0
Summer forage crops (raingrown)	0	0	5.00	0	0
Annual ryegrass in winter followed by a summer cereal forage crop (irrigated)	0	1.50	0.55	2.50	0
Perennial temperate pastures (irrigated)	0	0	1.00	3.60	0
Lucerne (irrigated and conserved)	0	0	0	0	2.65
Maize-barley crops (irrigated and conserved)	0	0	0	0	2.00
Total area	10.70	7.35	14.4	6.70	4.65

Table 3. Herd profile on 1 September 2001

Parameter	M1	M2	M3	M4	M5
Median age (years)	4.2	4.2	3.8	3.7	3.9
Previous mean milk production (L) (305 days) for multiparous animals	6160	6110	6411	6242	6988
Days in milk (mean/median)	44/42	146/158	203/166	162/151	139/159
Mean animal liveweight (kg)	520	550	570	520	570

where possible, mating commenced 1 month earlier in an attempt to reduce the number of animals needing to be mated between December and February inclusive.

The program commenced 30 days before the planned start of mating and followed principles developed in the national dairy cow reproductive management program InCalf (Morton *et al.* 2003) and included oestrus detection, use of heat mount detectors, veterinary examinations and treatment with controlled internal drug-releasing devices and prostoglandins. For the M5 herd, heat detection aids were applied to animals 40 days after calving. Animals showing signs of oestrus were inseminated on that day and mount detectors replaced. M5 animals not pregnant or unmated and 40 days after calving, were included in the intensive mating program. Cows in M1 to M4 herds that did not conceive in the mating season were replaced when ~305 days in milk with a pregnant heifer or, if all heifers had been allocated, a pregnant animal of similar age, liveweight and genetic merit to preserve the farmlet herd age structure. For the M1 herd, as part of a farmer-driven activity concerned with milk composition during the summer period, breed composition was changed in Year 4 with replacement animals (nine in total) being of Holstein-Friesian × Brown Swiss/Jersey breeding. For M5 animals that failed to become pregnant, the combination of days in milk (>300) and current production (<25 kg/day) were the key replacement criterion. These animals were replaced with a pregnant heifer or an animal of similar genetic merit and age due to calve in 60 days. This approach resulted in a wide inter-calving interval of 11–18 months.

For M1 to M4 herds, 25% of the herd was replaced each year with heifers while for M5 this increased to 33%. The seasonal calving pattern of farmlets was maintained by replacing animals that failed to conceive in the appropriate mating period. When additional replacements were required, multiparous animals were used. While the principal reason for culling was failure to become pregnant during the designated mating period, animals were also replaced on the basis of high somatic cell count (SCC), disease, physical injury, poor production and age. Where an animal died, it was replaced immediately with an animal of similar age and stage of lactation from the Mutdapilly herd. Actual annual replacement rates ranged from 40 to 55% and were much higher than the 25 (M1 to M4) and 33% (M5) envisaged.

Forage management

To achieve best management of the forage bases, land allocated to each farmlet herd was laid out in a manner that enabled best management of irrigation and grazing rather than being distinctly grouped. For example, four separate fields of 1.0–1.2 ha in size were dedicated to annual ryegrass pastures (Feedbase 4). Within each of these fields temporary fencing was used to allocate portions of land to the relevant herds. These herds grazed the one field before moving to the next field in synchrony. Following the grazing of a field, temporary fencing was removed and any necessary agronomic practices conducted across the whole field such as fertilising and irrigation. For the M5 herd, which had no requirement for grazing, the feedbase was co-located with other crops grown for hay and silage on the facility. The management of feedbases was based on a schedule of accepted industry best practices tempered by seasonal conditions, irrigation supply and labour constraints. Management responses were reviewed weekly. A general overview of management practices is detailed below. For all feedbases nitrogen (N) fertiliser was applied as urea with additional elements phosphorus (P), potassium (K) and sulfur applied as required on the basis of soil test results. The allocation of feedbases (ha) to each farmlet herd is given in Table 2.

Feedbase 1. Improved tropical grass (raingrown). Established rhodes grass (*Chloris gayana* cvv. Callide and Pioneer) was the dominant pasture. Urea was applied two or three times over the growing period (spring to late summer) at 50–100 kg N/ha on each occasion. The mean annual rate applied to pastures grazed by M1, M2, M3 and M4 herds were 240, 245, 190 and 175 kg N/ha respectively. Some conservation of forage surplus to grazing requirements was conducted in late summer of years 2004 and 2005.

Feedbase 2. Winter cereal forage crop (raingrown). Oats (*Avena sativa* cv. Nugene) at 50 kg seed/ha was established between March and June following a summer fallow. In Year 3 due to very low rainfall just over 50% of the crop area was sown. Fallow management involved two herbicide sprays, based on glyphosate, followed by one or two tillage operations. N fertiliser was applied at or before planting at 50 kg N/ha, and after each grazing at the same rate if another grazing was forecast. The mean annual rate applied was 50 kg N/ha.

Feedbase 3. Summer forage crops (raingrown). Forage sorghum (*Sorghum* spp. cv. Superdan) at 10 kg seed/ha and lablab (*Lablab purpureus* cv. Rongai) at 30 kg seed/ha were grown in separate fields. Each year two-thirds of the forage area was allocated to sorghum and one-third to lablab. Fields were rotated to ensure that 2 years of sorghum was followed by 1 year of lablab. N fertiliser was applied at or before planting to forage sorghum at 50 kg N/ha and after each grazing at the same rate if another grazing was forecast. Overall sorghum crops received a mean annual application of 90 kg N/ha. Opportunistic conservation of forage surplus to grazing requirements was conducted in late summer.

Feedbase 4. Annual ryegrass followed by summer forage crop (irrigated). Annual ryegrass (*Lolium multiflorum* cv. Tetila or Midmar) at 30 kg seed/ha and forage sorghum (*Sorghum* spp. cv. Superdan) at 15 kg seed/ha were grown sequentially with plantings in April and December respectively. Typically two to three cultivations were conducted between crops using disc implements and planting took place using a combine planter. The pasture and crops were rotationally grazed using back fencing. Paddocks were irrigated and fertilised, usually at 50 kg N/ha but sometimes at half rate on ryegrass, following each grazing rotation. Overall, Feedbase 4 received an annual mean application of 270 kg N/ha (range 230–300 kg N/year). Irrigation supplemented rainfall – particularly over winter and spring – with an annual mean application of 3.4 and 1.7 ML/ha to the winter and summer forages respectively. Opportunistic conservation of forage as round bale silage was undertaken in spring and late summer.

Feedbase 5. Perennial temperate pastures (irrigated). These pastures were based on lucerne (*Medicago sativa* cv. Sequel) at 8 kg seed/ha and ryegrass (*Lolium perenne* cv. Grasslands Impact) at 20 kg seed/ha or lucerne and prairie grass (*Bromus willdenowii* cv. Matua) at 30 kg seed/ha. Pastures were rotationally grazed using back fencing and strategically fertilised with urea. Irrigation was applied at an annual mean application of 4.3 ML/ha. With lower than average rainfall and reduced irrigation supply, the pasture swards became lucerne dominant as the study continued and N fertiliser inputs were reduced accordingly. The annual mean rate of application for pasture grazed by M3 and M4 herds were 40 and 85 kg N/ha respectively.

Feedbase 6. Lucerne (irrigated and conserved). *Medicago sativa* cv. Sequel was grown in a 3-year rotation with a maize-barley cropping phase. The lucerne seed was sown into a fully prepared seedbed at 15 kg/ha. It was cut for hay 6–7 times per year and received annual mean irrigation of 5.1 ML/ha.

Feedbase 7. Maize-barley double crop (conserved). Maize (*Zea mays*) was established using a precision planter on a 75-cm row spacing to achieve minimum plant populations of 60 000/ha. Plant varieties suited to specific regional conditions and silage production were used. The mean annual rate of N fertiliser and irrigation water applied was 200 kg N/ha and 2.5 ML/ha respectively. Crops were cut for silage when the grain milk line reached a midpoint on the kernel. Barley (*Hordeum vulgare* var. Kaputar) at 60 kg seed/ha was sown with a combine planter in mid-to-late May into maize stubble. It was fertilised at or soon after planting with a mean annual application of 57 kg N/ha. Irrigation was applied at a mean annual application of 1.2 ML/ha. year. Crops were cut for silage at the soft dough stage of grain development.

Nutritional management of lactating and non-lactating cows

In developing the farm models, annual inputs of feed (homegrown and purchased) were matched with annual requirements. As an added check on the feasibility of each farm, monthly assessment of feed inputs were calculated and also matched with monthly requirements (Callow *et al*. 2005). Grazing and conservation plans were developed on a week-by-week basis throughout the study. A flat rate of concentrate was fed to each herd but the mineral and protein contents were adjusted depending on seasonal conditions (Table 4). Large round bales of hay or silage were fed in ring feeders for the four grazing herds or as part of the total mixed ration for M5. All non-lactating cows were managed off the designated farmlet area except for cows from Farmlet 1, which remained within the farmlet area until 2 weeks before calving. In the 2 weeks before calving, all animals were moved to common calving paddocks where pellets were used for transition cow feeding. After calving, concentrates were increased to the required level during the first month of lactation.

Table 4. Typical daily grain mix (kg DM/cow) offered to lactating cows in the farmlet herds

Feedstuff	M1	M2	M3	M4	M5
Grain and minerals	4.41	4.77	6.74	7.02	5.76
Molasses	2.00	1.93	0	0	1.23
Protein meal	0.83	0.92	0.76	0.24	1.47
Whole cotton seed	1.50	1.69	1.50	1.69	1.60
Urea	0.05	0	0	0	0.08
Bicarbonate soda	0.18	0.18	0.18	0.18	0.20
Total	8.97	9.49	9.18	9.13	10.34

For the grazing herds 2 kg of grain mix was fed during each milking. The balance of the grain mix was fed to M3 and M4 herds in stalls immediately before, or proceeding, each milking while for M1 and M2 herds, a mix of molasses and grain with a small amount of hay was fed once per day in troughs within the feedbase. For the M5 herd the grain mix was fed within a total mixed ration. This herd was fed *ad libitum* twice daily with the amount of feed adjusted to achieve a 5% refusal.

Milking management

All the farmlet herds were milked through a 10-a-side, double-up, low-line dairy. The dairy was equipped with Westfalia Metatron (Germany) automated milk meters, automatic cow identification and automated concentrate feeding. For M1 to M4 herds, milking was conducted twice daily commencing at 0530 and 1430 hours. For M5 milking was at these times plus a third milking at 2130 hours.

Farmlet measurements

Milk production for each cow was recorded at each milking (Dairyplan 5, Westfalia) and a composite sample of the daily milk collected on one day each 14 days for analysis for protein, fat and SCC using Dairy Express Herd Recording Services (Wacol, Qld, Australia).

The liveweight of all individual cows was measured on a weekly basis using automatic scales linked to an automated recording system (Dairyplan 5, Westfalia).

During an intensive monitoring period between March 2002 and March 2003 (Barber 2008) all forages and concentrates used by each farmlet were sampled and analysed at Dairy One Forage Laboratory (Ithaca, New York State, USA) using either NIRS or wet chemistry analysis methods. Samples were dried in a fan-forced oven at 55°C for 48 h to determine DM content and prepare for processing. Silage samples were frozen immediately after sampling and dried at −40°C for 48 h in a vacuum-operated freeze drier. All feed samples were ground through a 1-mm sieve, following drying, then stored in airtight containers for shipping for analysis. Feed composition analyses included crude protein, neutral detergent fibre, acid detergent fibre, metabolisable energy and minerals. Following this period of intensive monitoring, feed analysis continued bi-monthly to assist in ration formulation. Supplementary feed for the grazing herds (M1 to M4), and all feed offered to M5, was weighed before feeding and visual estimates recorded of hay and round bale silage losses. It was considered that there was no significant wastage of concentrates but wastage of round bale hay and silage fed to M1 to M4 was estimated at 20% for high quality (lucerne, temperate pasture) and 30% for medium quality (forage sorghum), roughages respectively. This wastage is high relative to values of less than 10% given for high quality hay fed in ring feeders (Buskirk *et al*. 2003). It is attributed to the need to feed up to 4 days' supply at a time because of small herd sizes and the inherent greater wastage this entailed, particularly for silage (Martin *et al*. 2003), than for 1-day supply feeding.

Calculations

Milk production from home-grown forage (estimated)

For the grazing herds this was determined as the residual milk production after all supplements had been accounted for. Milk production from supplements, after allowing for wastage, was based on Kerr *et al*. (1999). The response rates, as part of a balanced diet, were: grain mix, 1 kg DM to account for 1.3 kg milk; high quality conserved fodder (lucerne or ryegrass hay), 1 kg DM to account for 0.9 kg milk; medium quality conserved fodder (vegetative forage sorghum hay), 1 kg DM to account for 0.7 kg milk.

Model of predicted weekly milk production

As a supplement to the study of annual production, an EXCEL spreadsheet model was developed to predict weekly milk production for each farmlet herd. The model used the number of cows calving each week over 4 years and a lactation curve ($y = 0.0003x^3 - 0.0315x^2 + 0.4471x + 28.365$ where y = daily milk yield; x = week of lactation) based on a high production herd at Mutdapilly (Orr *et al*. 1996). For each farmlet lactation curve, total production equalled the predicted production for animals in that farmlet with the curve scaled proportionally. To develop weekly production figures, a predicted calving pattern (PC), based on the premise that 50% of animals in herds M1 to M4 would calve in the first third of the calving period while animals in M5 would calve at regular intervals was used. During the course of the study weekly production was also predicted using the actual calving pattern (AC) of the farmlets.

Milk composition benchmarks

For milk protein and fat concentration, the standards of 3.1% (m/v) and 3.3% (m/v) were used respectively as regional processors may impose penalties below this level.

Nutrient use efficiencies and nutrient surplus

Annual N, P and K inputs and outputs were calculated for each farmlet. Inputs comprised inorganic fertilisers, purchased supplementary feeds and N fixation by legumes, which was estimated on the basis of forage yield (Walker *et al*. 2007) and a fixation value of 2% of herbage DM (Peoples and Baldock 2001). Milk (0.51% N, 0.09% P and 0.15% K) was the sole output with a steady-state assumed for animal liveweight and there was no export of feedstuffs or manure. Nutrient use efficiency (NUE) was calculated by expressing nutrient outputs as a percentage of inputs for each element and surpluses (inputs less outputs) expressed as kg/ha for each farmlet.

Assessment of annual and weekly production models

For annual production, the deviation of actual from predicted production was calculated for each year. For weekly production, deviations from predictions were identified from a visual assessment of graphs of weekly milk flow (actual and predicted). An analysis of modelling efficiency (Loague and Green 1991) between actual weekly milk production and predicted milk production based on PC or AC was determined using the statistical package GENSTAT 8 (GENSTAT 8 Committee 2005). In this analysis modelling efficiency is defined as a measure of the overall goodness of fit, with values close to one indicating a near-perfect fit (Mayer and Butler 1993).

Results

M1 rain-grown, pasture-based system

Production

Mean annual milk production was 6330 kg/cow and 12 030 kg/ha, 12.7% below predicted levels (Table 5). In Years 1–4, production was 15.3, 3.5, 11.4 and 20.5% below predictions respectively (Fig. 2). Highest production coincided with a year of favourable winter rainfall (Year 2) and lowest production with changes to herd breed composition (Year 4). Monthly milk composition reflected the herd's seasonal calving pattern. Milk protein while relatively high during late lactation in autumn and early winter, fell below the industry benchmark (3.1%) on 47% of sampling occasions (Fig. 3). Milk protein output averaged 375 kg/ha.year. Milk fat percentage also showed marked seasonality, being low in early lactation and high, up to 5%, in late lactation, but remained above benchmark levels throughout the year. Modelling efficiency for weekly herd milk production was 0.20 and 0.75 (Table 6) when PC vs AC patterns were used. Deviations were greatest in Year 1 and 4 due to potential production being reduced by cows entering the trial part way through their lactation (mean 60 days in milk, Year 1) and changes to herd breed composition (Year 4). In Years 2, 3 and 4 bringing forward the mating period to minimise the effects of summer heat stress resulted in actual production being advanced on predicted production. SCC was in a normal range. Annual mean liveweight remained relatively stable over Years 1, 2 and 3 but fell in Year 4 with changes to herd breed composition (Fig. 2). There was a general pattern of losses in early lactation and gains in late lactations, but this was not consistent and strongly influenced by seasonal conditions.

Reproduction

All animals were mated during the summer mating period, with the result that 40% of animals typically failed to conceive within the designated mating period (Table 5). Overall mean 21-day submission rate (SR) was reasonable at 77% but the first-service conception rate (CR) and 6-week in-calf rate (ICR) of 27 and 42% were well below the industries benchmarks of 53 and 71% achieved by the top quartile of Australian farms

Table 5. Predicted[A] and actual input and output parameters for the five farmlets

Parameter	M1		M2		M3		M4		M5	
	Predicted	Actual	Predicted	Actual	Predicted	Actual	Predicted	Actual	Predicted	Actual
Milk production										
Stocking rate (head/ha)	1.9	1.9	2.7	2.7	1.4	1.4	3.0	3.0	4.3	4.3
Milk yield (kg/cow.year)	7250	6330	6757	6730	7520	7078	7313	7617	9620	9457
Milk yield (kg/ha.year)	13 780	12 030	18 920	18 840	10 530	9830	21 940	22 850	41 370	40 670
Milk yield (kg/ha.year) from home-grown forage[B]	–	4200	–	7100	–	4400	–	11 500	–	–
Mean milk fat (%)	–	4.08	–	4.03	–	4.00	–	3.90	–	4.01
Mean milk protein (%)	–	3.12	–	3.14	–	3.15	–	3.18	–	3.18
Mean milk lactose (%)	–	5.00	–	4.97	–	5.00	–	5.03	–	5.00
Milk solids (fat + protein) (kg/ha.year)	–	866	–	1351	–	703	–	1618	–	2924
Purchased grain, fodder and fertiliser										
Grain mix (t DM/cow.year)	2.86	2.74	2.47	2.89	2.53	2.80	2.04	2.78	2.87	3.15
Medium quality hay/silage (t DM/cow.year)	1.0	1.2	0.9	0.9	0.9	0.35	0	0	0	0
High quality hay (t DM/cow.year)	0	0	0	0	0	0	1.1	0.30	0	1.50
Fertiliser nitrogen (kg/ha.year)	255	196	276	258	88.5	83.2	168.7	167.0	160.0	99.0
Fertiliser phosphorus (kg/ha.year)	7.6	12	20.3	14.4	4.1	11.9	22.0	19.0	5.7	5.9
Fertiliser potassium (kg/ha.year)	43.3	12.5	57.7	13.5	23.0	5.5	62.5	9.0	32.6	14.5
Irrigation										
Total annual water (ML)	0	0	8.7	6.9	8.3	6.0	36.7	26.1	28	19
Water applied to irrigable area per year (ML/ha)	0	0	5.8	4.6	5.4	3.9	6.0	4.3	6.0	4.1
Irrigable area (ha)	0	0	1.5	1.5	1.55	1.55	6.1	6.1	4.65	4.65
Annual exit data (% of herd)										
Failure to conceive during set mating period	–	41	–	32	–	39	–	24	–	22
Culled for other reasons	–	15	–	17	–	13	–	13	–	22
Deaths	–	0	–	3	–	1	–	2	–	1
Total	25	56	25	52	25	53	25	39	30	45
Other										
Mean somatic cell count (×1000)/mL	–	260	–	259	–	261	–	231	–	236
Mean cow liveweight (kg)	–	540	–	546	–	562	–	561	–	608

[A]For some parameters there was no predicted value.
[B]Calculated for farmlets M1–4 as per Kerr *et al*. (2000).

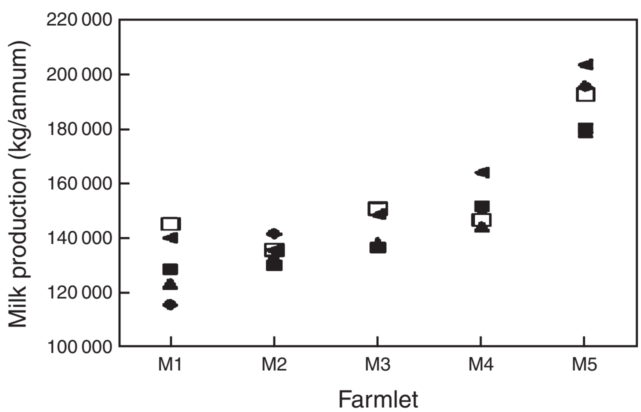

Fig. 2. Annual milk production per farmlet (kg) relative to predicted production (□) for year 1 (▲), year 2 (◀), year 3 (■), year 4 (◆).

(Morton 2004). Overall losses of animals from the system exceeded 50% each year.

Supplementary feeding

Hay was fed at a higher rate than predicted while the grain mix was within predicted levels (Table 5). Hay was fed at particularly high levels in the early phases of the study (2.3 t hay equiv./cow in Year 1) but declined substantially by Year 4 to 0.6 t/cow reflecting seasonal conditions and improved management of the forage base and hay feeding practices. In Years 3 and 4 some surplus forage was conserved as hay at the rate of 0.4 and 0.6 t/cow respectively and fed back to save on purchases. The amounts of purchased hay and grain supplements fed were sufficient to account for ~65% of milk production.

Nutrients

Fertiliser N was applied at 75% of the predicted rate in response to the generally poor seasonal conditions while P and K were applied at rates above and below budget (Table 5). Supplementary feed was an important source of nutrients entering the farming system, with 46, 69 and 90% of purchased N, P and K entering by this means (Table 7). NUE was 16, 27 and 15% and nutrient surplus, as expressed on a per hectare basis, was 319, 30 and 106 kg for N, P and K respectively.

M2 limited irrigation, pasture-based system

Production

Mean annual milk production of 6730 kg/cow and 18 840 kg/ha was recorded, and was very close to overall

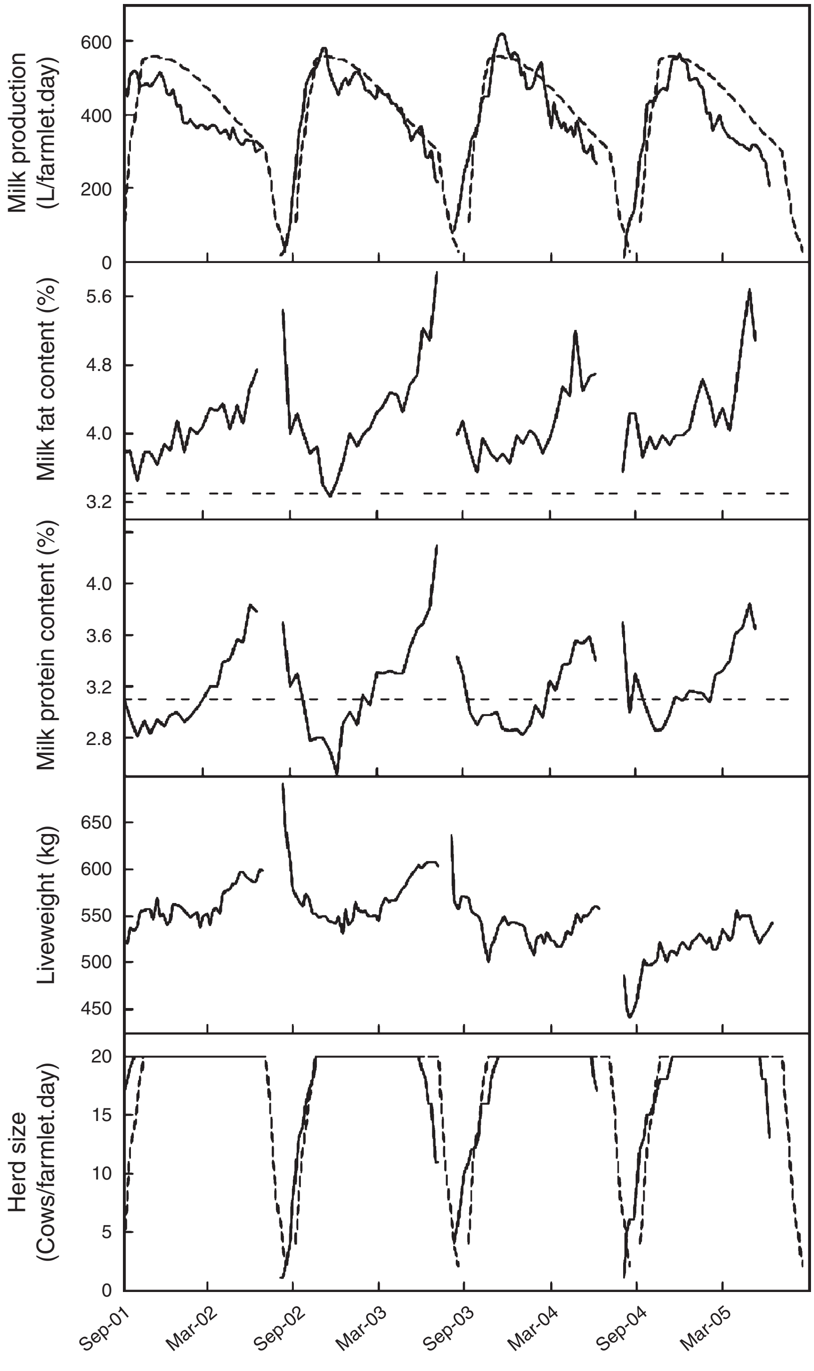

Fig. 3. M1 production parameters (—) in relation to model predictions (- -) for milk production and cow numbers or industry standards (- - - -) for milk fat and protein content.

predictions at just 0.4% below (Table 5). On an annual basis production was –2.2, 0.2, –4.1 and 4.4% above predicted levels (Fig. 2). Production at the lowest times of the year, late summer and early spring (Fig. 4), was approximately half that at the peak periods of production, autumn and late spring. Milk protein percentage showed variation from 2.8 to 3.4% and fell below the industry benchmark (3.1%) on 37% of sampling occasions. Most deficits occurring during spring and summer (Fig. 4) and high values were recorded in winter and autumn. Milk protein output averaged 590 kg/ha.year. Milk fat was always above industry standards. Calving pattern was responsible for 50% of the deviation between predicted and actual weekly milk production (Table 6). Other factors influencing weekly model efficiency were cows' stage of lactation when they entered the farmlet (Year 1) and the effect seasonal conditions had on production in all years. Seasonal impacts were particularly noticeable in Year 3 when production fell substantially lower than anticipated; possibly triggered by the very hot weather in the

Table 6. Analysis of modelling efficiency between actual weekly milk production and predicted milk production using the predicted calving pattern (PC) or the actual calving pattern (AC)
Modelling efficiency (R^2 from line $y = x$)

Year	M1		M2		M3		M4		M5	
	PC	AC	PC	AC	PC	AC	PC	AC	PC	AC
1	–0.16	0.43	0.52	0.48	0.51	0.79	0.56	0.70	–0.13	0.27
2	0.66	0.93	0.02	0.69	0.32	0.74	0.26	0.56	–0.33	–1.24
3	0.66	0.92	0.01	0.50	0.16	0.49	0.42	0.54	–0.07	0.36
4	0.16	0.57	0.10	0.75	0.50	0.77	0.61	0.80	–0.01	0.44
All	0.20	0.75	0.18	0.67	0.37	0.70	0.49	0.67	–0.01	0.28

Table 7. Nutrient balance (kg/ha equiv.) and nutrient use efficiency (%) as calculated for the three major plant nutrients (N, P and K) for each farming system

	M1	M2	M3	M4	M5
Nitrogen (N)					
Fertiliser	197	251	84	167	99
Purchased feed	181	255	114	239	577
N_2 fixation	0	0	29	72	138
Less milk output	–59	–91	–49	–113	–202
Balance	319	415	178	364	603
Use efficiency (%)	16	18	22	24	25
Phosphorus (P)					
Fertiliser	12	14	12	19	6
Purchased feed	29	43	22	44	106
N_2 fixation	0	0	0	0	0
Less milk output	–11	–16	–9	–20	–36
Balance	30	41	25	43	76
Use efficiency (%)	27	28	26	32	32
Potassium (K)					
Fertiliser	13	13	6	9	15
Purchased feed	111	149	31	75	201
N_2 fixation	0	0	0	0	0
less milk output	–18	–27	–15	–34	–60
Balance	106	135	22	50	156
Use efficiency (%)	15	17	41	40	28

preceding January and February (Fig. 4). SCC was in a normal range. Animal liveweight showed expected variation associated with two calving periods each year, with low values in early spring and autumn and high values in summer and winter. The typical autumn weight loss in 2004 (Year 3) was greater than anticipated and coincided with lower than expected milk production (Fig. 4). An underlying cause of this reduction in productivity was the carry over effects of a particularly hot and wet late summer.

Reproduction

Overall 30% of animals failed to conceive during the designated mating periods and were removed from the herd (Table 5). While SR were similar in summer and winter (82 and 87% respectively), first-service CR was lower in summer (18 vs 53%) and 6-week ICR was also lower at 33 vs 63%. Overall losses from the system each year were 52%.

Supplementary feeding

Grain mix inputs were higher (0.4 t DM/cow.year) than predicted, while purchased hay inputs were similar (Table 5). Additional home-grown forage was conserved as hay, and fed back as required, at a mean rate of 0.4 t DM/cow.year. Purchased supplements accounted for ~62% of total milk production. Irrigation inputs were ~80% of that predicted due to restrictions in water allocation as a result of ongoing drought in the catchment.

Nutrients

Fertiliser N inputs were similar to that predicted, but P, and particularly K, somewhat lower (Table 7). Supplementary feed was an important source of nutrient input, with 50, 75 and 92% of purchased N, P and K entering the farm by this means (Table 7). NUE was 18, 28 and 17% and nutrient surplus as expressed on a per hectare basis was 415, 41 and 135 kg for N, P and K respectively.

M3 limited irrigation, crop-based system

Production

Mean annual milk production was 7078 kg/cow and 9830 kg/ha, 6% below predicted production (Table 5). Over Years 1–4, production was 8.3, 1.4, 9.2 and 9.1% below predicted levels (Fig. 2). Highest and lowest production coincided with years of favourable (Year 2) and unfavourable (Years 1, 3, 4) winter rainfall with production during Year 3 being particularly low and potentially impacted on by preceding summer conditions. Milk protein percentage showed substantial variation, ranging from 2.8 to 3.5%, around the mean of 3.15%. It fell below the industry benchmark (3.1%) on 38% of sampling occasions with the more protracted deficits generally occurring during autumn and early winter (Fig. 5). Milk protein output was 310 kg/ha.year. Milk fat showed modest variation around the mean of 4% and the SCC was within industry expectations. Following a wet and very hot late summer in Year 3 (2003–04), animal liveweight dropped substantially, but otherwise showed modest variation around a mean of 562 kg. When error generated by calving pattern was removed, modelling efficiency for weekly herd milk production was relatively high (Table 6) in all years except Year 3. In this year very low production during winter was an important

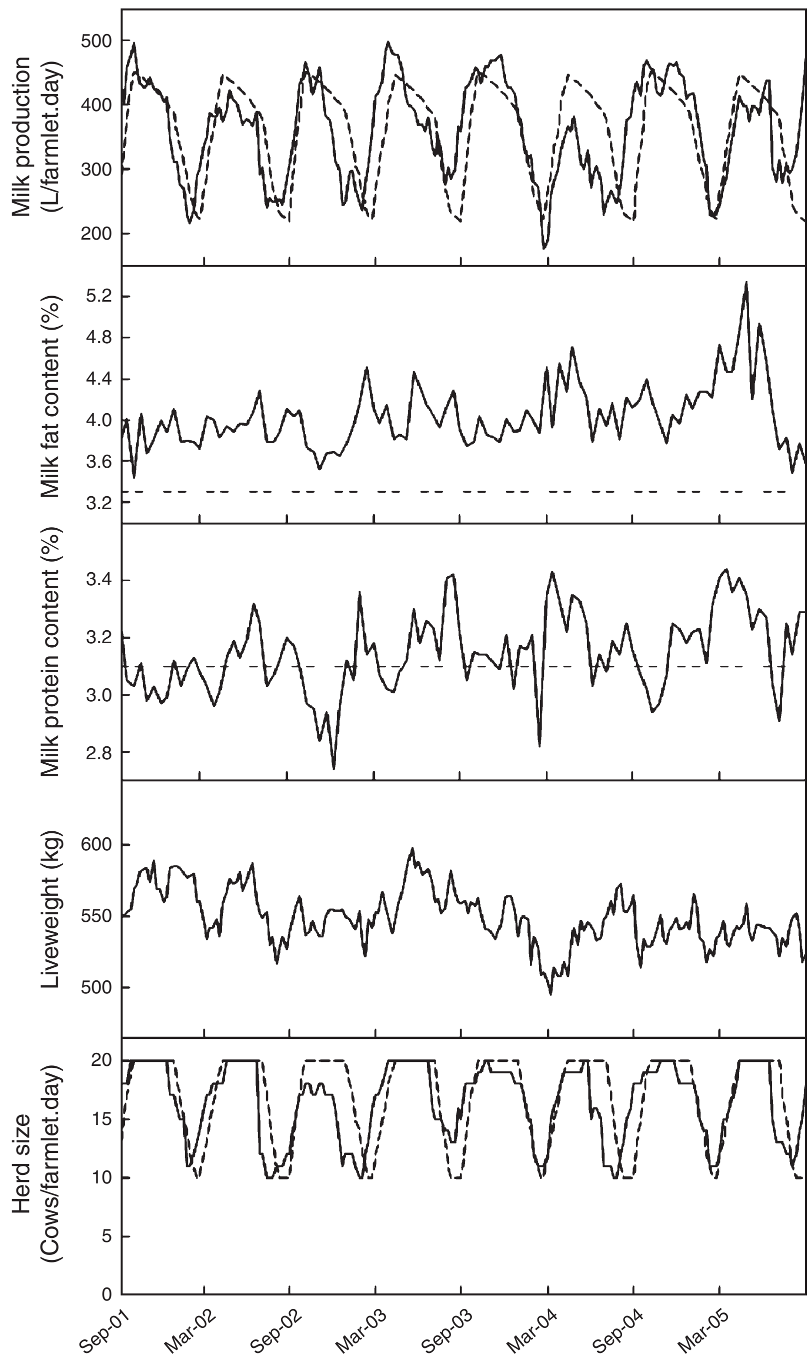

Fig. 4. M2 production parameters (—) in relation to model predictions (- -) for milk production and cow numbers or industry standards (- - - -) for milk fat and protein content.

factor, while influencing all years was a consistent pattern of animals drying off earlier than predicted.

Reproduction

Overall 40% of animals failed to conceive during the designated summer and winter mating periods (Table 5). An overall mean 21-day SR of 84% and first-service CR of 56% met industry benchmarks but the 6-week ICR (60%) did not (Morton 2004).

Supplementary feed

Purchased grain mix was higher and hay inputs lower than the predicted allocation (Table 5). Purchased grain and hay supplements were sufficient to account for ~55% of milk

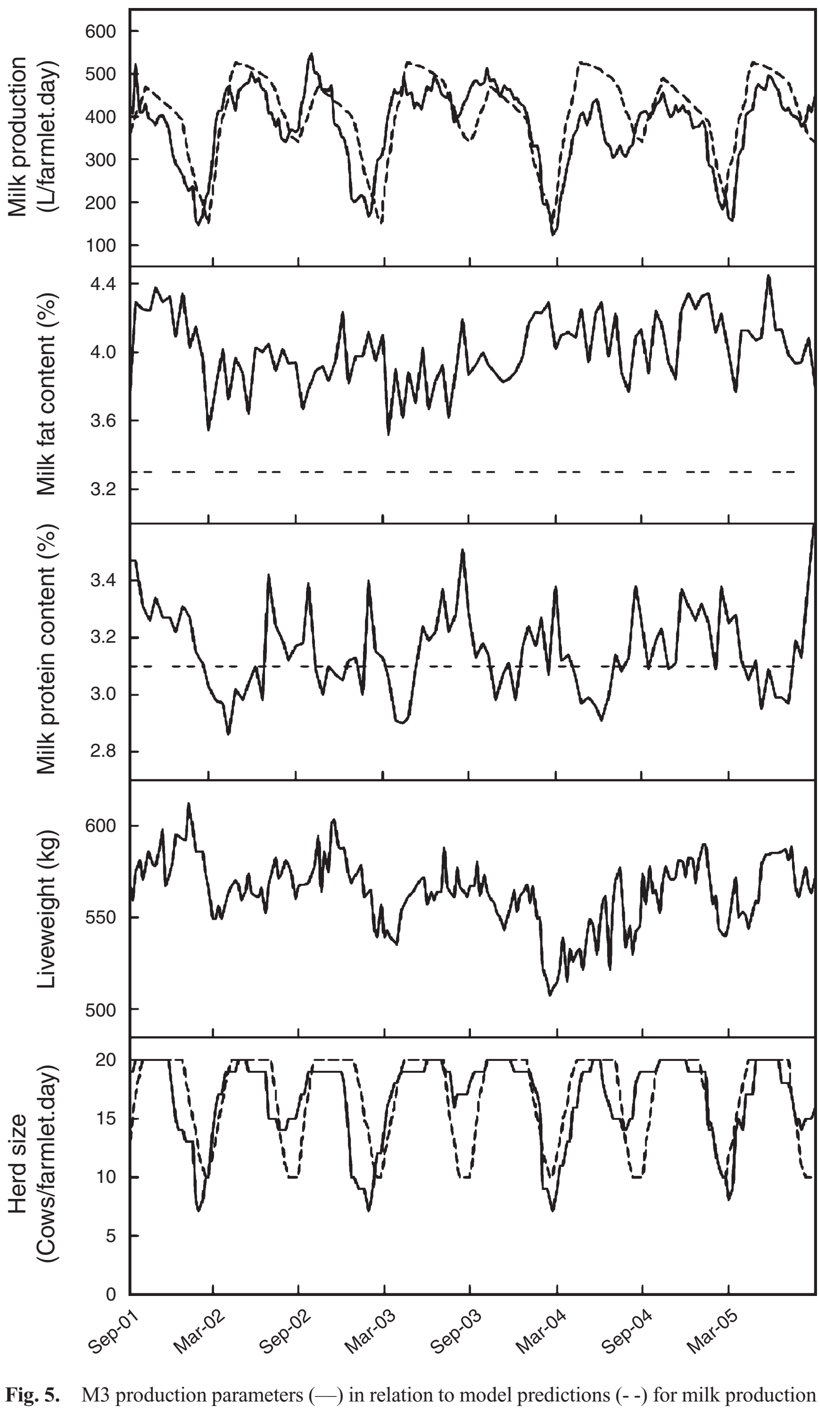

Fig. 5. M3 production parameters (—) in relation to model predictions (- -) for milk production and cow numbers or industry standards (- -   - -) for milk fat and protein content.

production. Additional hay from forage sorghum, in excess of daily requirements, was conserved and fed back to animals. The mean annual rate of conservation was 0.85 t DM/cow.year. Conservation was highest in Year 3 at 1.4 t DM/ha and lowest in Year 2 at 0.37 t DM/ha. These years coincided with high and low summer rainfalls respectively. Irrigation inputs were restricted to a small portion of the farm forage area (11%) planted to annual ryegrass and over sown with forage sorghum. Four ML/ha of irrigation was applied to this area each year, 72% of the predicted allocation.

Nutrients

Fertiliser inputs for N were similar to the predicted allocations while P inputs were higher and K lower (Table 7). Supplementary feed was an important source of nutrients, contributing 50, 65 and 85% of N, P and K entering the farm, and legumes were estimated to contribute 13% of total N inputs. NUE was 22, 26 and 41% and nutrient surplus expressed on a per hectare basis was 178, 25 and 22 kg for N, P and K respectively.

M4 high irrigation, high quality, pasture-based system

Production

Mean annual milk production was 7617 kg/cow and 22 850 kg/ha, 4.2% above predicted production (Table 5). Production was 1.8% below and 12.0, 3.5 and 2.9% above predicted levels in Years 1–4 respectively (Fig. 2). The highest production period (Year 2) coincided with a year of better winter rainfall while production during winter of Year 3 fell below predicted levels and coincided with low winter rainfall, limited irrigation and a greater than expected decline in production and liveweight late in the preceding summer (Fig. 6). Milk protein output averaged 705 kg/ha.year, ranging from 2.9 to 3.5% of milk volume and falling below the industry benchmark (3.1%) on 27%

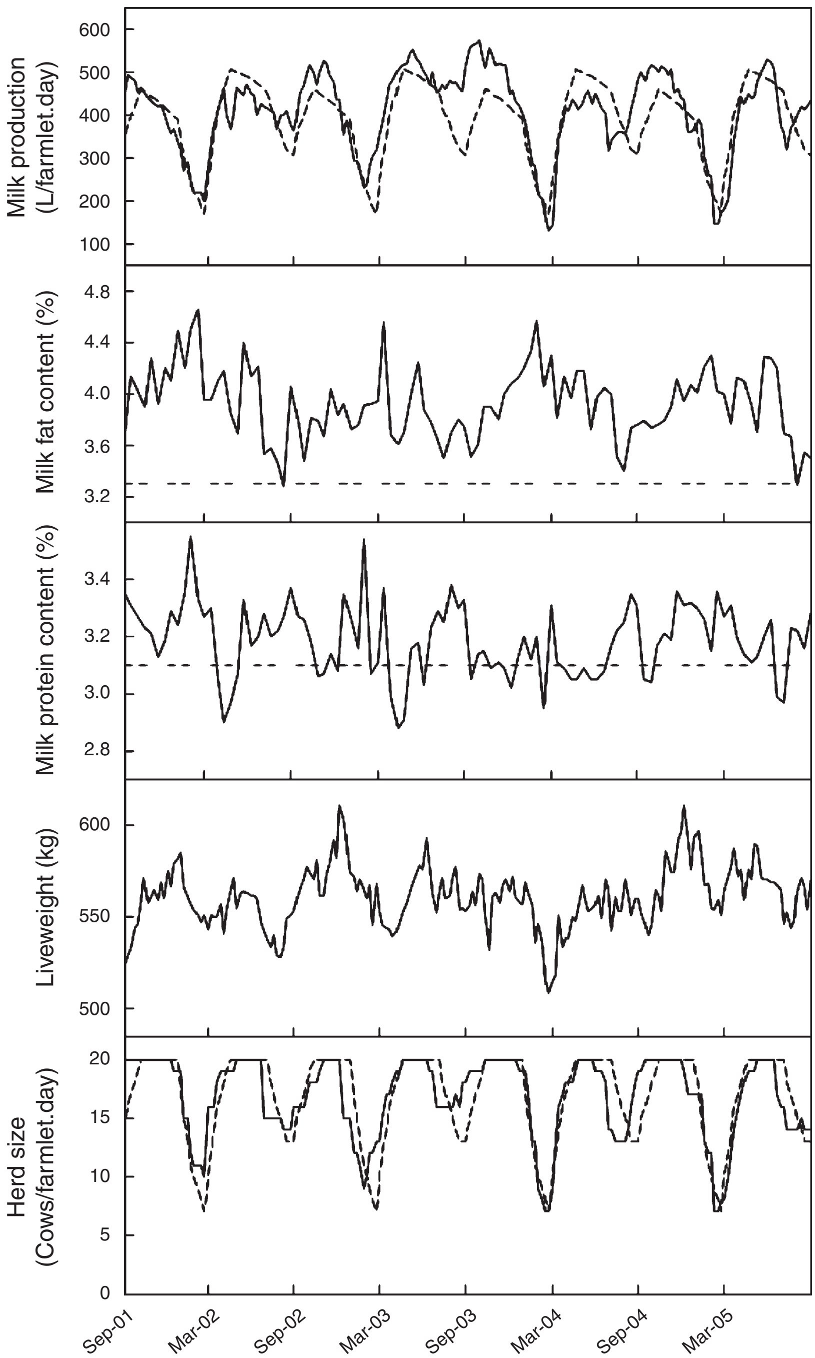

Fig. 6. M4 production parameters (—) in relation to model predictions (- -) for milk production and cow numbers or industry standards (- - - -) for milk fat and protein content.

of sampling occasions with deficits more common in autumn and early winter (Fig. 6). Milk fat was always above industry standard. The mean SCC was acceptable. Mean annual animal liveweight remained relatively stable over the course of the study (Fig. 6). When PC pattern was replaced with AC pattern, efficiency of the weekly milk production model (Table 6) improved in all years – particularly Year 2. However, efficiency was still low in Year 2 when production substantially exceeded predicted supply and in Year 3 when it fluctuated above and below predictions in Year 3.

Reproduction

Overall, 24% of animals failed to conceive during the designated summer or winter mating periods. When compared against set industry benchmarks, reproductive performance was favourable with a 21-day SR (89%) and first-service CR (55%) meeting benchmarks established for the top quartile of farms. The 6-week ICR of 67% did not meet this benchmark but still exceeded that typically achieved (63%) on farms (Morton 2004).

Supplementary feed

Purchased grain mix inputs were substantially higher (plus 0.74 t/cow.year) than the predicted allocation but this was offset by feeding a smaller amount of hay (Table 5). Additional hay made from forage sorghum, in excess of daily requirements, was conserved and fed back to animals. The mean annual rate of conservation was 0.85 t DM/cow.year. Conservation was highest in Year 3 at 1.4 t DM/ha and lowest in Year 2 at 0.37 t DM/ha, coinciding with high and low summer rainfall respectively. This forage was mostly fed back to the herd in autumn and early winter. Purchased hay and grain supplements fed to the herd were sufficient to account for ~50% of milk production. This indicates a relatively high level of milk production coming from home-grown forage at ~11.5 t DM/ha. year (Table 5).

Nutrients

Fertiliser inputs for N and P were similar to the predicted allocations while K was lower (Table 7). Supplementary feed was an important source of nutrients, contributing 50, 68 and 89% of N, P and K entering the farm. Legumes were estimated to contribute 15% of total N inputs. NUE was 24, 32 and 40% and nutrient surplus expressed on a per hectare basis was 364, 43 and 50 kg for N, P and K respectively.

M5 irrigation, feedlot

Production

Mean annual milk production was 9457 kg/cow and 40 670 kg/ha, 1.7% below predicted production (Table 5). In Years 1–4 production fluctuated between –7.4, 5.6, –6.5 and 1.4% of predictions (Fig. 2). High production in Year 2 was attributed to better farming conditions and the production of better quality forage while in Year 3 a substantial decline in per cow production, recorded during very hot weather in January and February 2004, contributing to lower than expected production (Fig. 7). Milk protein percentage fell below the industry benchmark (3.1%) on 33% of fortnightly milk recordings and mean values were close to industry standard. Milk protein, in relation to the forage production area, was high at 1293 kg/ha.year. Several factors contributed to the very low modelling efficiency for weekly herd milk production (Table 6). The most important was a marked deviation in milking cow numbers from the very constant number predicted (Fig. 7). The weekly milk production model was based on evenly spaced all year-round calving with a 13.5-month inter-calving interval. However, despite mating animals year-round this did not occur due to low CR in summer and the inclusion of M5 animals in the intensive mating program. This led to a concentration of animals calving in autumn. When PC date was replaced with AC date modelling efficiency improved somewhat, however, the highly variable inter-calving interval of 11–18 months still contributed to keeping modelling efficiency low.

Reproduction

Twenty-two percent of animals were removed from the herd for failure to conceive before or during the following intensive summer or winter mating program. Animals included in the intensive mating programs achieved high SR of 85% (no difference between seasons). There was some indication of seasonal affects on conception with a 6-week ICR of 50 vs 63% for summer and winter matings respectively.

Supplementary feed

Conserved forage and grain mix needed to be fed at 1.5 and 0.28 t DM/cow.year respectively above that predicted in the desktop model (Callow *et al*. 2005) to achieve milk production targets (Table 5). This was due to an underestimation of herd requirements (26 kg DM/animal.day vs desktop model prediction of 22 kg DM/animal.day) and some shortfall in forage production due to limited irrigation supply.

Nutrients

Fertiliser inputs for N and K were substantially less than predicted while P applications were as predicted (Table 5). Supplementary feed was a very important source of nutrients (Table 7) contributing 72, 95 and 93% of N, P and K inputs respectively. Legumes were estimated to contribute 17% of total N inputs. NUE was 25, 32 and 28% and nutrient surplus, as expressed on a per hectare basis, was 603, 76 and 156 kg for N, P and K respectively.

Discussion

Environment

The study was conducted under more adverse environmental conditions – lower average annual rainfall, higher summer temperatures and restricted irrigation – than were anticipated when the alternative farming systems were modelled (Callow *et al*. 2005). These changed conditions had a generally negative impact on forage productivity, in particular rain-grown crops and pastures, due to extended periods of moisture stress and reduced opportunities to plant crops (Webb *et al*. 1997). Higher than expected summer temperatures would also have exacerbated difficulties with reproductive performance (Morton *et al*.

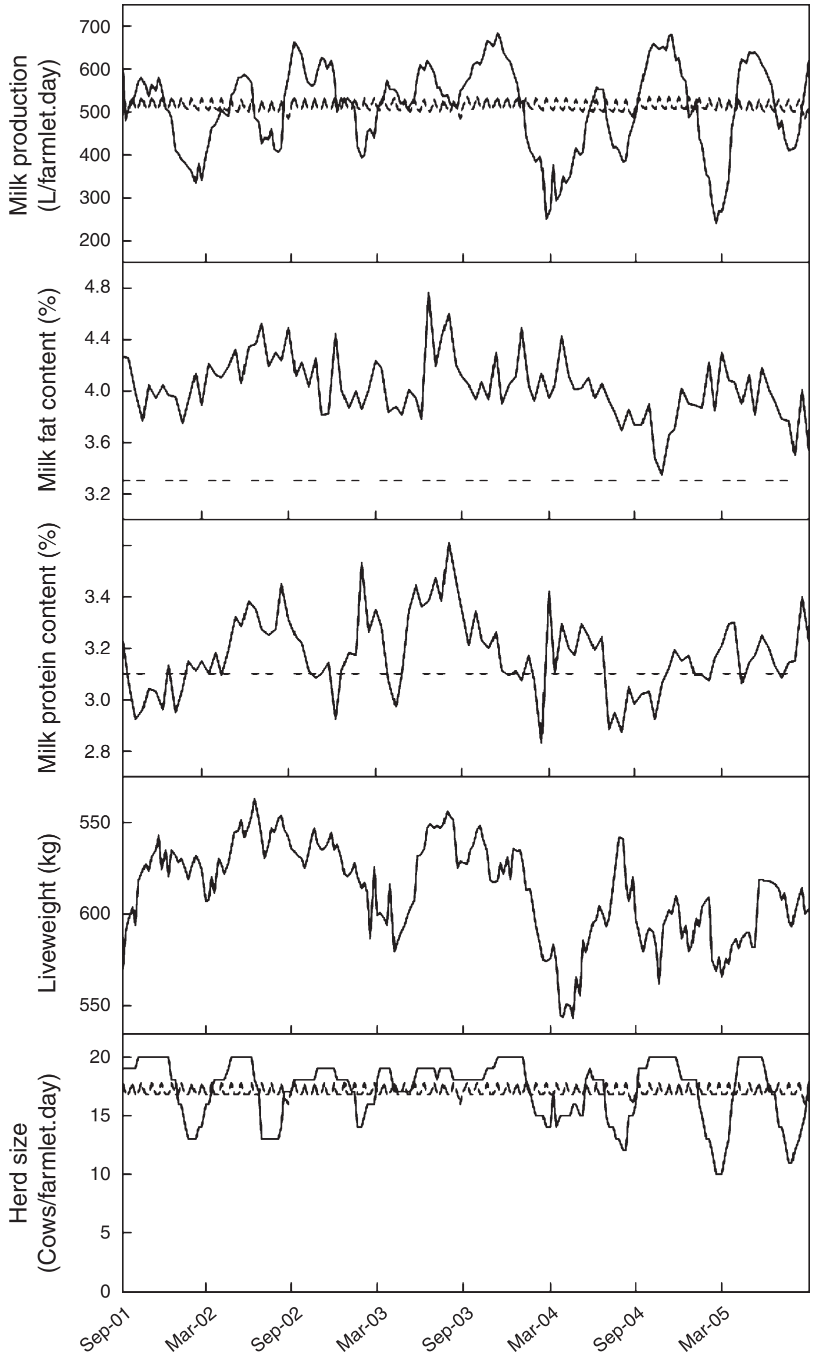

Fig. 7. M5 production parameters (—) in relation to model predictions (- -) for milk production and cow numbers or industry standards (- - - -) for milk fat and protein content.

2007) and further reduced animal feed intake (Beede 1986). Tempering these negative outcomes was the reduced incidence of waterlogged soils, which is a particular limitation of the study site (Fisher and Baker 1989), and the probable reduction in the incidence of diseases such as mastitis and lameness which are more prevalent under wet, muddy conditions (Tranter and Morris 1991; Harmon 1994). In summary, we believe the conditions had a generally negative impact on the largely rain-grown M1, M2 and M3 while the impact on the higher irrigation systems, M4 and M5, was mixed.

Efficacy of production models

A purpose of the study was to assess the applicability of the desktop model developed by Callow *et al.* (2005) for high milk production systems in the subtropics. Over the study period, by making generally modest changes in the mix of inputs – less fertiliser and more hay and/or grain to offset rainfall and irrigation limitations, production of 87.3, 99.6, 94.0 and 104.2%, of that predicted was achieved for M1 to M4 respectively. However for M5, due in part to limited experience with this style of farming, a substantial quantity of high quality hay and some additional grain had to be purchased to achieve 98.3% of predicted milk production. For all systems there was general failure to anticipate the high percentage of cow replacements required due to reproductive failure within targeted mating periods.

The closest overall level of agreement between desktop model inputs and outputs was M2 while M4 exceeded predicted production, particularly during Year 2 under more favourable environmental conditions. For M1 and M3, whose actual production fell short of predicted production overall, the outcome indicates a possible overestimation of potential for these systems. Heavy reliance on winter rain-grown forage made them particularly vulnerable to rainfall deficits over this period with production being closest to that predicted during the more favourable conditions of Year 2 (Fig. 2). For M3, low winter rainfall was exacerbated by a shortfall in predicted irrigation supply in Years 3 and 4. For M5 the model's limitation was primarily due to an underestimation of the herd's forage requirements rather than a failure in field production. In contrast, the higher production of M2 and M4 suggest the model underestimated the potential of these systems under improved circumstances. To further assess potential yields, the decision support tool DAIRYPRO (Kerr *et al*. 1999) was used to analyse productivity of the four grazing systems. It suggested that given the inputs of fertiliser and supplementary feed, matched with the relevant feedbases, the farmlets achieved 85 (M1) and 95% (M2, M3 and M4) of their expected potential production. M1 is identified again as a system that underperformed in this study. We attribute this largely to the lower than average rainfall exacerbated by changes in herd composition in the last year of the study. A weakness of the desktop model was its inability to consider the impact of more or less favourable climatic regimes on forage production. Reliance on single-value predictions of forage production, based on mean seasonal conditions, is limiting in the northern Australian dairy industry where coefficients of variation for annual rainfall typically range from 25 to 30% (Clewett *et al*. 2003). With respect to the high replacement rate across all systems, other authors have noted the potential reproductive constraints of Holstein-Friesian cattle in seasonal 12-month calving systems (Fulkerson *et al*. 2001; Borman *et al*. 2004); particularly when summer mating is involved (Morton *et al*. 2007).

Achieving a forecast level of daily milk production, to avoid penalties, is now a requirement of particular processors in northern Australia as sales of drinking milk in Queensland exceeds total production (Anon. 2008). The weekly Excel milk production model (Table 6) illustrates how critical calving pattern is in achieving predicted weekly or daily milk supply. This factor was more important than seasonal conditions in causing deviations from the predicted weekly production. While reproductive management techniques used in this study were based on sound principles (Morton *et al*. 2003), and implemented by trained staff, they were still inadequate in addressing the broader issue of reproductive constraints of Holstein-Friesian cattle in a subtropical environment. This issue requires further analysis and investigation.

Production in the subtropics

The study demonstrated the capacity of intensive farming systems located in the subtropics to achieve moderate to high milk production per cow and per hectare, and at levels above that generally achieved in commercial practice (Busby *et al*. 2006; Anon. 2008). Analysis of farm data in the subtropics, where milk production is predominantly based on the Holstein–Friesian breed, has consistently shown per cow production of at least 6200 kg/cow.year to be associated with more profitable enterprises (Busby *et al*. 2006). All faming systems achieved above this level of production at 6330–9460 kg/cow.year and production per hectare of 9800–40 700 kg/year. Production from forage (calculated) for the grazing systems (M1 to M4) was similar or lower on a per cow basis than previous studies in northern Australia (Davison *et al*. 1985; Ashwood *et al*. 1993; Walker *et al*. 1993; Cowan *et al*. 1995*c*) while production per hectare (Table 5) indicated a high level of utilisation; given the rainfall and irrigation constraints.

For the M1 system, milk production per cow and per hectare was higher than achieved in an earlier study on the same site (Cowan *et al*. 1995*b*) and associated with the higher level of supplementary feed. For home-grown forage only, there was a reduction in milk produced on a per cow basis but production per hectare was higher (120%). This production was still only half that achieved in a higher rainfall (1250 mm/year) upland environment (Davison *et al*. 1985), indicating the potential under improved farming conditions. The M2 system, which is the most common style of farming in northern Australia (Callow *et al*. 2005), achieved high productivity per hectare through its combination of a perennial tropical grass feedbase, irrigated annual temperate forages (20% of the forage base) and high levels of supplementary feeding. The contribution a small area of irrigated temperate forages can make to milk production in northern Australia, particularly through winter, is well recognised (Kaiser *et al*. 1993) and was probably an important factor in the achievements of this farming system. In relation to productivity from home-grown forage Walker *et al*. (1993), using a similar farming system, but in a higher rainfall tropical upland environment, achieved annual production from pasture of 4650 kg/cow and 8250 kg/ha – 180 and 115% of what was achieved in this study. In this study, Walker *et al*. (1993) noted that pasture on offer in all years was high and there was potential to increase the stocking rate further. For the M3 system, which was developed for the lower rainfall Darling Downs region of southern Queensland, per cow and per hectare productivity was 90 and 100% respectively of that of a hypothetical system proposed by Ashwood *et al*. (1993). Given the unexpected restrictions on irrigation entitlement in this study, this farming system may have benefited from replacing perennial temperate pastures (two-thirds of its irrigation area) with the more water use efficient double crop annual ryegrass-summer cereal combination (Walker *et al*. 2007). The M4 system achieved high annual productivity per cow and per hectare with ~4000 kg/cow and 11 500 kg/ha coming from forage. This approaches levels recorded in environments that are more temperate. In Hamilton, New Zealand, Macdonald *et al*. (2008) recorded milk yields of 11 100, 11 750 and 12 700 kg/ha from Holstein–Friesian cows grazing ryegrass and white clover pastures under stocking rates of 2.2, 2.7 and 3.1 cows/ha (no grain supplementation). In southern Australia, King and Stockdale (1980) recorded higher levels of production of 16 000 kg/milk.ha from Jersey-Friesian cross cows managed on irrigated perennial pasture at a stocking rate of 6.6 cows/ha (no grain supplementation). Also in southern Australia, Valentine *et al*. (2009) recorded almost double the total milk yield (~40 000 kg/milk.ha) from animals grazing irrigated perennial ryegrass-based pastures (5.2 cows/ha) and heavily supplemented. In this latter study estimated yield from pasture was 14 000 kg/milk.ha. As for M3, a greater emphasis in M4 on annual ryegrass double-cropped to forage sorghum over the less water use efficient perennial temperate pasture mix may have been beneficial to milk production. With respect to M5, despite facility limitations in terms of cooling (no sprinklers or fans) and being unable to manage the herd in multiple groups on the basis of stage of lactation, the M5 herd experienced a large and rapid increase in milk yield (38% improvement) in the first 12 months of the study. It then sustained this higher level of production through the course of the study. The ability of dairy animals in the subtropics to rapidly increase production when a more favourable environment is created was also noted by Orr *et al*. (1996) with animals achieving the same proportional rise in productivity after being moved from a lower input pasture-based system to a semi-feedlot system. In our study, following this rapid rise in production, the herd maintained high levels of production over the following 3 years. We attribute this improved, and relatively high, productivity per cow to improvements in ration and rumen function (Garcia and Fulkerson 2005), reduced energy demands of grazing (NRC 2001), more frequent milking (Erdman and Varner 1995) and better management of heat stress (Grainger *et al*. 1996). However, feed conversion efficiency (FCE), uncorrected for residuals and wastage, was relatively low. Average daily production over the course of the study for lactating animals from the M5 herd was 30 kg/day of energy corrected milk (ECM) (Tyrell and Reid 1965) giving a FCE for offered feed (26 kg DM/animal.day) of 1.15 ECM/kg feed DM. This efficiency is similar to that which has been measured in on-farm monitoring of herds fed total mixed rations by Quinn *et al*. (2004), as cited by Beever and Doyle (2007), but less than the 1.36 (range 1.11–1.67) measured by Britt *et al*. (2003) in the southern USA and Mexico. In the latter study, negative relationships of feed efficiencies with such factors as dietary fibre, days in milk and higher ambient temperatures were found. Oetzel (1998), cited by Britt *et al*. (2003), suggest that the feed efficiency for healthy and well managed herds should fall in the range of 1.3–1.5 solids-corrected milk per kilogram of DM intake. This suggests scope for improvement in the biological and feeding management of the M5 herd.

Milk composition

All farmlet herds failed to consistently meet the industry milk protein standard of 3.1% (m/v) crude protein. However, frequency of failure, mean protein concentration and protein yield varied. On these three measures, the study indicated the particular vulnerability of the M1 system and the potential of the M4 and M5 systems to achieve well. Features of the M1 herd, which disposed it to poorer milk protein attributes, were; the amplification of stage of lactation affects due to seasonal calving (Auldist *et al*. 1998), the relatively lower quality diet as a result of a greater emphasis on tropical grasses (Beever *et al*. 2001), and the increased impact of heat stress on milk yield and protein concentration (Armstrong 1994; Mayer *et al*. 1999) due to most animals being in early and mid lactation during summer. For the M2 herd, which shared a relatively strong emphasis on tropical grass pastures and spring calving, summer was also the main period of milk protein limitations, while in contrast M3, with a greater emphasis on winter calving and a higher quality summer forage base, experienced most milk protein failures in autumn and early winter. Mean milk protein concentration was generally higher for the M4 and M5 herds. Barber (2008), in a more detailed study of the farmlets between March 2002 and 2003, noted that animals in M4 consumed a higher and more consistent energy-dense ration than the other grazing herds. Over the course of the current study the average milk protein concentration recorded in Queensland and Victoria was 3.17 and 3.32% true protein (m/v) respectively (Anon. 2008). All of the herds therefore fell short of the Victorian values and only M4 and M5 exceeded the Queensland mean values. Achieving acceptable levels of milk protein in a subtropical environment will always present challenges because of the quality of tropical forages and heat stress. A strong emphasis on summer calving will exacerbate deficiencies.

Reproduction

All farmlet herds had a high percentage of cows exit due to a failure to conceive during a set mating period (22–41%). Replacement rates due to reproductive failure in other farmlet studies have been less (Fulkerson *et al*. 2008; Macdonald *et al*. 2008) though Valentine *et al*. (2009) recorded a 21-week ICR of only 63% for irrigated farmlets in southern Australia. The general difficulties in achieving satisfactory CR in seasonal 12-month calving Holstein-Friesian herds is well recognised (Fulkerson *et al*. 2001; Auldist *et al.* 2007) and is commonly attributed to higher milk yield potential than other breeds and ready mobilisation of body reserves in early lactation to sustain yields (Fulkerson *et al*. 2001). In our study, these breed limitations appeared to be more pronounced over the summer mating period. For animals in the grazing farmlets (M1 to M4), we recorded little difference in 21-day SR between winter and summer matings (87 vs 82%) but the 6-week ICR fell from 67% in winter to 45% in summer. In an earlier study at Mutdapilly Research Station Orr *et al*. (1996) found that cows artificially inseminated in winter (July–September) had a mean pregnancy rate of 79% compared with 58% for animals inseminated in summer (December–February). In a tropical upland environment, Orr *et al*. (1993) found that the pregnancy rate in cows and heifers fell from 80 to 55% as mean daily maximum temperature increased from 26°C to 27.5°C. The authors concluded that achieving consistently high pregnancy rates would require the removal of both heat and nutritional stress during the summer months. Also in the same upland environment Morton *et al*. (2007) found that while the effects of heat load on CR was greatest in the week leading up to, and in the week after service, rates were affected by heat up to 5 weeks before service. These findings suggest that a seasonal mating program over summer, such as was attempted with M1, will fail. For all herds, suboptimal mating outcomes will be likely over summer and mating should be minimised, or cease altogether during this period. For the M5 herd, which had a more flexible mating program and an inter-calving interval up to 18 months, replacement rate due to reproductive failure was generally lower than the grazed herds but was still relatively high at 22%. Again, summer was a more difficult period than winter. However, the M5 farming system has greater potential than the grazing systems to improve cooling over summer through interventions (shade, sprinklers, and forced ventilation). For all herds, extending the length of lactations by delaying breeding until the period of negative energy balance is past warrants consideration. A longer inter-calving interval has the potential to reduce reproductive failure (Borman *et al*. 2004), improve animal welfare (Knight 2001) and give a more consistent supply of milk with minimal impact on annualised milk yield (Auldist *et al*. 2007).

Nutrient use efficiency and surplus

Purchased supplementary feed was the major contributor to nutrient input, accounting for about half the N, two-thirds of P and most of the K coming into the grazing systems (M1 to M4). For the feedlot system (M5) the proportional contribution was higher. The situation for the grazed systems is more typical of Europe (Netherlands, Denmark) than traditional year-round grazing systems of New Zealand (van Keulen *et al*. 2000; Ledgard *et al*. 2004) and rain-grown farms in southern Australia (White and Gourley 2001). However, nutrient surpluses of a similar magnitude to this study have been noted in studies of future irrigated farming systems in southern Australia (Ho *et al*. 2002; Valentine *et al*. 2009). In the latter study, where dairy cows were supplemented with ~2.5 and 1.5 t DM/year of concentrate and roughage respectively and managed under stocking rates of 2.5–7.4 cows/ha, annual surpluses ranging from 200 to 1000 kg N/ha, 40 to 410 kg P/ha and 50 to 300 kg K/ha. Large surpluses are indicators of environmental risks (Hutson *et al.* 1998) and Valentine *et al.* (2009) questioned the sustainability of the most intensive farming systems in their study when large surpluses combined with a build up of soil minerals. In our study, while nutrient surpluses were not of the magnitude as those reported by Valentine *et al.* (2009), they are of a level that warrants further investigation in terms of potential environmental risk.

In relation to particular nutrients, as farms intensify and N inputs increase, despite an increase in milk production, there will be a general decline in NUE and increase in N surplus. Ledgard *et al*. (2004) compared intensive farming systems using nil vs 400 kg N/ha and found that NUE fell from 43 to 23% and N surplus increased from 92 to 387 kg/ha. van Keulen *et al*. (2000) noted that in the Netherlands as fertiliser and concentrate increased between the 1950s and 1980s NUE fell from 46 to 16% and the surplus increased 10-fold. Developing strategies to improve NUE and reduce surpluses for all farming systems is challenging. On a typical Midwest (USA) dairy farm Wattiaux *et al*. (2005) found that while management practices could be altered to eliminate half of whole-farm P surplus with minimal impact on farm income, only 5% of N surplus could be eliminated with the same impact on income. In our grazed farming systems (M1 to M4), there may be potential for refinement of N fertiliser rates as they were often developed under conditions of lower stocking rates (Cowan *et al*. 1995*a*) and as a result, lower rates of manure and urine deposition. The routine feeding of higher levels of conserved fodder would also warrant greater effort to reduce wastage, and, there is some potential to refine rations and minimise surplus N in diets by monitoring milk urea N (Jonker *et al*. 2002).

With respect to P, surpluses in this study were similar or less than other Australian studies (Ho *et al*. 2002; Valentine *et al*. 2009), and there is potential to reduce them further by refining fertiliser rates and dietary P (Wattiaux *et al*. 2005). For K, conserved forage imported into all the systems brought substantial amounts onto the farm. Gourley (2004) found that when increased stocking rates (2–3 cows/ha) coincided with dry seasonal conditions, K surplus rose and NUE fell from 51 to 28%. In our study, low efficiencies and high surpluses were characteristic of farmlets that used high levels of purchased forages and molasses (M1, 2 and 5).

The spatial distribution of nutrients also needs consideration. Apparent benefits of a low nutrient surplus, expressed on a per hectare basis, will be much less if nutrients are not well distributed. Gourley *et al.* (2007) notes that heterogeneous distribution of nutrients is common on Australian dairy farms. The potential limitations of grazed systems – particularly those that are feeding high levels of supplements such as M1 to M4 – means that a well managed feedlot (M5) may provide better control over the capture, redistribution (and removal if necessary) of nutrients from the farm. If nutrient surpluses cannot be adequately managed through good redistribution, or removed from the farm when the landscapes capacity to store them is exceeded, then a reduction in purchased inputs, which will inevitably lead to a lower stocking rate, may be unavoidable if surpluses have to be reduced to meet community concerns. For example, to meet water quality standards in the Lake Taupo catchment, New Zealand (Edgar 1999), ground water standards in Europe (van Keulen *et al*. 2000), and most recently the Great Barrier Reef lagoon, Australia [*Great Barrier Reef Protection Amendment Act 2009* (Qld)], specific land management practices have been legislated.

Conclusion

The field testing of the desktop model, developed as a ‘rapid response’ to assist farmers modify current farming systems in response to the constraints of a deregulated industry, affirmed the capacity of farming systems located in the subtropics to achieve moderate to high milk production levels both on a per cow and per hectare basis. This indicates a substantial increase in milk output from dairy farms can be realised. Reasonable agreement between the field and desktop model for the grazed systems was achieved, but there was an underestimation in the daily feed requirements of the feedlot herd (M5). The model was limited for all systems by its static approach to rainfall variation and failure to predict the high level of reproductive failure over the summer mating period. The development of calving schedules that enable predicted weekly milk production targets to be achieved while minimising animal wastage needs to be pursued as does strategies to manage nutrient surpluses.

Acknowledgements

We thank all other staff at Mutdapilly Research Station for their contribution to this project, in particular Mr Lex Turner, Ms Patricia Skele and Mr Terry McAllister. Thanks to Mr Kevin Lowe for assistance with the preparation of figures and Dr Tom Cowan for reviewing drafts of this paper. We are grateful for the financial support provided by Dairy Australia.

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Manuscript received 24 September 2009, accepted 17 March 2010