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Dairy Deregulation and Low-Input Dairy Production: A Bioeconomic Evaluation

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Deregulation of the Australian dairy industry could affect the utilization of resources by milk producers and the profitability of dairy production. In this study we examine the feed mix that dairy producers use, both pastures and supplements, under partial and total deregulation. We are particularly interested in the interaction of pasture utilization and farm profitability. The results of this research demonstrate that profitable low-input dairying is constrained by the most limiting resource, feed supplied by pasture, and that the interactions between economic and biological processes are critical to farm profitability.

Key words: bioeconomics, dairy production, deregulation, low-input dairying, pasture utilization

Introduction

Low-input dairying is an emerging pasture-based milk production technique designed to avoid high feed, labor, and capital costs (Forgey and Forgey). In traditional high-input operations utilized by many producers in North America, cows are either tethered in stalls or kept in large barns and fed a ration of hay, or silage, and some form of concentrate (Grant and Keown). There is growing anecdotal evidence that low-input dairying can be more profitable than traditional methods in particular circumstances (Harlow; Forgey and Forgey). Due to such positive experiences, U.S. dairy producers increasingly see pasture-based grazing, together with changes in herd and feed management, as a means of keeping production costs down and remaining in the industry (Forgey and Forgey; Stallings). Given recent reductions in the prices U.S. producers receive for milk, particularly milk used in processed products, low-input dairy production may become an increasingly viable economic option.

Our objective is to supplement this anecdotal evidence with a rigorous examination of low-input dairy production. Such an examination requires an extension to traditional pasture modeling found in the literature. Previous pasture modeling efforts have focused on rangeland stocking operations whose objective is for cattle to achieve some desired weight per head over the growing season (Torrell, Lyon, and Godfrey; Karp and Pope; Huffaker and Wilen). In contrast, we are interested in the interactions between

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pasture productivity and milk yield in an intensive-grazing situation. In a pasture-based dairy system there is not an infinite amount of pasture available due either to the biological processes of the plant components within the system or to limitations of the land area. This differs from previous dairy supply research in which milk producers are assumed to have access to an infinite supply of purchased feed (Chavas and Klemme; Gao, Spreen, and DeLorenzo; LaFrance and de Gorter).

The biological heart of an economic dairy system model is the milk yield function mapping feed and other inputs into the herd's milk production. We follow Gao, Spreen, and DeLorenzo in taking a bioeconomic approach that formulates the milk yield function from its biological underpinnings, rather than the statistical approach taken in most economic dairy studies. Such studies typically estimate linear or quadratic yield functions (see, e.g., Chavas and Klemme; LaFrance and de Gorter). The milk yield function formulated in our fully pasture-based dairy system model incorporates all the biological systems of a dairy farm into one equation describing milk production as the excess of pasture and supplemental energy supplied over that demanded for all of the herd's nonlactating physiological demands.

This milk yield function is incorporated into an optimal control model representing the management problem of a representative low-input Australian dairy operation. The model, solved as an empirical nonlinear programming problem (Howitt), is used to examine the bioeconomic conditions for which low-input dairying is profitable and to determine the Australian producer's optimal response to a number of deregulation scenarios.

Australia provides an ideal case study area for analyzing the adoption of low-input dairy production systems. Australian dairy producers already use pasture-based systems to some extent, so there is a substantial amount of data available on pasture dynamics, milk production from pasture, and the interactions of pasturing and milk yields. Also, there is a renewed interest in further lowering milk production inputs due to proposed changes in dairy regulations. Thus, we are faced with a unique opportunity to examine both low-input dairy production and some interesting policy implications concurrently.

Although our pasture-based dairy system model is calibrated for a representative operation in New South Wales, the model itself is an algebraic representation of the herd and pasture dynamics characterizing such systems in general. Consequently, we expect that the model can be modified and calibrated for use in analyzing the issues surrounding the adoption of low-input dairying in other areas of interest, including the United States.

Australian Dairy Policy

The Australian dairy industry is subject to a relatively high level of government regulation, and the state of New South Wales (NSW) is among the most regulated. There are only two classes of milk in NSW, market and manufacturing. Market milk is fluid milk for human consumption, and manufacturing milk is used in the manufacture of dairy products such as cheese, yogurt, skim milk powder, or butter. The principal form of regulation in NSW is individual producer quotas on the supply of market milk (Tozer 1993a). The quota policy does not restrict production of milk, only the amount of market

milk sold at the regulated price. Producers receive a regulated price from the NSW Dairy Corporation (NSWDC) for their quota milk. For milk supplied in excess of quota, they receive a manufacturing milk price determined by market conditions and milk composition (Tozer 1993a). The regulated price for market milk is at a substantial premium to the manufacturing milk price. Currently, the premium is approximately $AUS 0.20–0.25 per liter depending on the month of production (NSWDC).

The state government is presently investigating deregulation of the industry to improve economic efficiency within the dairy industry and to reduce government programs in compliance with the GATT resolution and the recommendations of the National Competition Policy contained in the Hilmer Report (Hayman; McQueen). Deregulation of the dairy industry is expected to reduce the revenues of dairy producers, as the price received for market milk is expected to fall significantly when the government removes or reduces the legislated price premium for market milk (Hayman). To remain competitive under deregulation, producers need to consider ways of reducing the costs of production (MacAulay). One means of reducing costs is to replace the use of expensive supplemental feeds (e.g., grains and commercial preparations) with a fully pasture-based milk production system.

The aspect of deregulation particularly worrying producers in NSW is the proposal to phase out the market milk price premium (Hayman). With this in mind, we examine pasture-based dairying as an optimal feeding management response to full deregulation (no market milk premium), and to partial deregulation (a market milk premium allocated among producers based on market demand for fluid milk rather than a supply quota, i.e., blend pricing). A blend price is a weighted average price based on the revenue from the sale of milk to different markets with varying prices (Sumner and Wolf).

The Pasture-Based Dairy Control Model

We model an existing 42-hectare (ha) dairy operation located 250 kilometers from Sydney in the Hunter Valley, and fully described in Tozer (1993b). The breeding herd is made up of the "milking herd" composed of those cows currently producing milk and the "dry herd" composed of those cows that are in calf again but are not currently producing milk. The operation is split between a "pasture feeding area" (40 ha) where some portion of the breeding herd grazes, and a "supplemental feeding and milking area" (2 ha) where the portion of the breeding herd not on pasture is fed purchased supplements and where the milking herd is milked. Animals not currently in the breeding herd (i.e., replacement heifers and heifer calves old enough to graze) are kept on a portion of the farmer's land holdings separate from the dairy operation (e.g., rough pasture).

The pasture feeding area is composed of two perennial forages and two annual forages in a fixed five-year rotation. The rotation is defined by two years of pure alfalfa followed by two years of alfalfa undersown with perennial ryegrass and white clover, and in the final year forage oats are sown for winter forage followed by forage sorghum for summer forage. This final year is designed to provide a break from alfalfa (thereby reducing the problems of disease build-up in the soil) and to grow crops utilizing the stored soil nitrogen fixed and accumulated by the alfalfa in the previous four years.

The animal stocking rate on pasture is measured as the average rate over all forage types. Forage that is not consumed by grazing animals in a given period is cut and fed to them in other periods when forage production is low (e.g., winter). Thus, cows on pasture are fed fresh grass and/or conserved hay.

Given that the pasture rotation is fixed, the dairy farmer controls only the animal stocking rate on pasture and the level of supplements fed off pasture. The state variables in the dairy system are forage availability on pasture and the size of the breeding herd that evolves each period from an exogenously determined initial level. Assuming that the dairy farmer exerts the above controls to maximize the net present value of the dairy operation, the mathematical representation of this problem is:

$$(1)\qquad \underset{S,X_e}{\text{Max}}\, NPV = \sum_{t=1}^{T}\sum_{m=1}^{12} b(t,m)\{\pi_{I,m}[S_m, X_e, H_m, E_m] + \pi_{L,m}[H_m] - C_{E,m}[S_m, X_e, H_m] - C_{P,t}\},$$

subject to:

$$(2)\qquad H_m - H_{m-1} = \sum_{j=2}^{5}\left(1 - \delta_{j,c} - \delta_d\right)\left(H_{j-1,m-12} - H_{j-1,m-24}\right);$$

$$(3)\qquad E_m - E_{m-1} = \sum_{x=1}^{4}\{[a_{x,m-1}E_{x,m-1} - b_{x,m-1}(E_{x,m-1})^2] - [q(1 - \exp(-K * E_{x,m-1}))S_{m-1}] - [CE_{x,m-1}]\}A_{x,t};$$

$$(4)\qquad E_{e,m} = \left(H_m - S_m A\right)X_e;$$

$$(5)\qquad E_{S,m} = E_m + E_{e,m} + \gamma CE_m;$$

and

$$(6)\qquad E_{S,m} \geq E_{D,m}, \quad E(t=0) = E_0, \quad H(t=0) = H_0.$$

We first define the functions in equations (1)–(6) in general terms, and then provide details regarding functional forms and parameter definitions below. The objective functional is defined over a multiple-year (t) planning horizon, and each year nests a number of monthly (m) operations. The function $\pi_{I,m}[S_m, X_e, H_m, E_m]$ measures the monthly net revenue from milk production and depends on the pasture stocking rate control variable S_m [head/hectare (hd/ha)], the supplemental energy control variable X_e [megajoules per head (MJ/hd)], the herd size state variable H_m (hd), and the total pasture energy state variable E_m (MJ). The function $\pi_{L,m}[H_m]$ measures the monthly net revenue from livestock trading activities. $C_{E,m}[S_m, X_e, H_m]$ measures the costs of supplemental energy and is a function of the two control variables and the herd size state

variable. $C_{P,t}$ measures the annual costs of pasture sowing and maintenance. These quantities are discounted at rate $b(t, m)$.

Equation (2) calculates the monthly transition of the breeding herd among j age classes. Equation (3) measures the monthly net rate of change of energy as the difference between the production and consumption of energy from four pasture and forage types, where $A_{x,t}$ denotes the area of pasture x in year t. Equation (4) calculates the amount of supplemental energy the farmer purchases each month, and is a function of the control variables and the herd size state variable. Equation (5) determines the total energy available in any one month; the first two terms are defined by equations (3) and (4), and the final term is the amount of conserved hay energy fed. Equation (6) ensures there is sufficient energy available to at least satisfy the demands of the dairy herd. The parameters E_0 and H_0 are initial stocks of pasture energy and the dairy herd, respectively.

The discrete optimal control problem defined by equations (1)–(6) is solved as a nonlinear programming problem (Howitt; Standiford and Howitt). This approach allows great flexibility in nesting biological processes into the monthly intervals of the year for which they are operative, and in modeling variables that depend on events occurring outside the nested periods. For example, the milk produced by the farm in March this year depends on the number of cows that calved in January to March this year, as well as cows that calved from June until December last year. Each component of the dairy control problem is discussed in detail below.

Herd Dynamics

The equation of motion for the breeding herd [equation (2)] is derived as the first difference of

$$H_m = \sum_{j=2}^{5} \sum_{k=12}^{23} \left(1 - \delta_{j,c} - \delta_d\right) H_{j-1,m-k} \tag{7}$$

and measures the size of the breeding herd in month m. Age class $j = 2$ represents heifers entering the breeding herd for the first time. Age classes $j = 0, 1$ are calves and replacement heifers not yet old enough to enter the breeding herd, respectively. Cows older than $j = 5$ are culled due to falling milk production. Although the younger age classes $j = 0, 1$ are not included in the breeding herd, an equation similar to (7) keeps track of them in the model because they are the source of replacements into the breeding herd. The index k captures the lag in the recruitment process and runs from 12 to 23 months. This lag represents the months over which recruits are eligible to be in age class j (van Arendonk). The summand calculates the recruits entering class j in month m as the number of recruits in class $j - 1$ ($H_{j-1,m-k}$), less the number of culls ($\delta_{j,c} H_{j-1,m-k}$) and deaths ($\delta_d H_{j-1,m-k}$) in month m, where the proportional culling rate parameter $\delta_{j,c}$ varies across age classes and the proportional death rate parameter δ_d is constant across classes.

Livestock Revenue

Livestock revenue, $\pi_{L,m}$, is generated from the monthly sale of cull cows, bull calves, and heifer calves deemed to have more value in beef than dairy production:

$$\pi_{L,m}(H_m) = P_{bc}(0.5\alpha_c H_m) + \delta_{0,c} P_{hc}(0.5\alpha_c H_m) + P_b \sum_{j=2}^{5} \delta_{j,c} W_j H_{j,m}. \tag{8}$$

The first term accounts for the monthly profits from selling bull calves, where P_{bc} is the slaughter value for each animal, $\alpha_c H_m$ measures the number of calves born each month at the annual per capita calving rate α_c, and $0.5\alpha_c H_m$ measures the number of bull calves born each month given the common assumption that births are equally divided between the sexes. The second term accounts for the monthly profits from selling heifer calves for beef, where P_{hc} is the slaughter value for each animal, and $\delta_{0,c}(0.5\alpha_c H_m)$ measures the number of heifer calves sold given per capita culling rate $\delta_{0,c}$. Finally, the third term accumulates the profits from cull cow sales from each age class, where P_b is the price per kilogram received, W_j is the weight per cow in each age class, and $\delta_{j,c} H_{j,m}$ is the number of culls from each age class given the age-specific per capita culling rate $\delta_{j,c}$.

Energy Demand

The demand for energy by an individual cow depends upon her physical size and the time interval since she last calved. Assuming that a dairy cow has a 12-month calving cycle (van Arendonk), and that $k = 0$ is the month the cow calves, allows us to define three distinct physiological stages. The nonpregnant and lactating (NP) stage occurs over the interval $k = 0-2$ during which the cow requires energy for maintenance (M), $NE_{M,j,k}$, and milk production (L), $NE_{L,j,k}$. The cow generates some of her energy from body reserves, which causes weight loss in the first three periods of lactation (Goodall and McMurray). We account for this weight loss (G) as a negative energy demand, $NE_{G,j,k} < 0$. The pregnant and lactating (PL) stage begins in period $k = 3$ and continues until the cow is dried off at $k = 9$. During this interval, the cow demands energy for maintenance, lactation, and fetal growth (F), $NE_{F,j,k}$. The cow gains weight during this interval, requiring energy $NE_{G,j,k} > 0$. The pregnant and dry (PD) stage occurs over periods $k = 10, 11$, during which the cow demands energy for fetal growth, maintenance, and weight gain.

The total energy (E) required by cows in each of the three physiological stages is calculated using equations (9)–(11):

$$E_{NP,m} = \alpha_c \sum_{j=2}^{5} \sum_{k=0}^{2} \left(NE_{M,j} + NE_{L,j,k} + NE_{G,j,k}\right) H_{j,k}, \tag{9}$$

$$E_{PL,m} = \alpha_c \sum_{j=2}^{5} \sum_{k=3}^{9} \left(NE_{M,j} + NE_{L,j,k} + NE_{G,j,k} + NE_{F,j,k}\right) H_{j,k}, \tag{10}$$

and

$$E_{PD,m} = \alpha_c \sum_{j=2}^{5} \sum_{k=10}^{11} \left(NE_{M,j} + NE_{G,j,k} + NE_{F,j,k}\right) H_{j,k}. \tag{11}$$

For cows to enter the breeding herd, they must have calved; thus the number of cows in each physiological stage depends on the calving rate, α_c. Cows that do not calve are not

included in the energy demand calculations for the dairy because they are removed from the herd. Also note that the energy required for maintenance depends on the weight of the cow and not the time after calving [Ministry of Agriculture, Fisheries, and Feed (MAFF)]; hence the k subscript is omitted on $NE_{M,j}$.

If we sum the nonlactation energy demands and the number of cows in each class, we can show that total energy demanded by the whole breeding herd is:

$$E_{D,m} = \eta_{NP,m} + \eta_{PL,m} + \eta_{PD,m} + \alpha_c \sum_{j=2}^{5} \sum_{k=0}^{9} \tau L_{j,k} H_{j,k}, \tag{12}$$

where $\eta_{NP,m}$, $\eta_{PL,m}$, and $\eta_{PD,m}$ represent the nonlactation energy demands for each respective physiological stage, and the last term represents the total energy required to produce milk. We derive the last term by substituting $NE_{L,j,k} = \tau L_{j,k}$, where τ is the energy content of milk (MJ/liter), and $L_{j,k}$ is the milk yield per head of a cow in class j that calved k months ago. Multiplication by $H_{j,k}$ (number of cows in each class that calved k months previously) converts the last term into the energy units (MJ) consistent with the rest of equation (12).

Equation (12) can be solved for the herd's total milk production in m, Y_m (liters):

$$Y_m = \left(E_{D,m} - \left(\eta_{NP,m} + \eta_{PL,m} + \eta_{PD,m}\right)\right)/\tau, \tag{13}$$

where

$$Y_m = \alpha_c \sum_{j=2}^{5} \sum_{k=0}^{9} L_{j,k} H_{j,k}. \tag{14}$$

According to equation (13), total milk yield can be calculated as the difference between the total energy demanded by the herd and the energy required for nonlactation purposes, normalized by the energy content of a liter of milk.

Energy Supply

Equation (3) sums the monthly net rate of change in the energy supplied by four pastures indexed by x. The first square-bracketed term in the summand measures the production of energy on pasture x (MJ/ha) with a logistic growth function. The logistic function often is used to measure the growth of forage dry matter (Noy-Meir; Huffaker and Wilen). Given that well-managed forages have relatively constant energy contents (Lazenby), energy production is measured proportionate to forage production and expressed using the same functional form. The second bracketed term in the summand measures the monthly consumption of pasture energy by the breeding herd (MJ/ha) using the exponential form of the Michaelis function (Bhat and Huffaker). This function is asymptotic at the monthly satiation level of a cow, q (MJ/hd). The parameter K is inversely related to the cow's grazing efficiency and is assumed to be constant over the herd. The stocking rate S_{m-1} (hd/ha) converts consumption of pasture energy per head into consumption by the entire herd. The third bracketed term, $CE_{x,m-1}$ (MJ/ha), accounts for the hay that is made from excess forage and fed out when fresh forage production is

low. Finally, multiplying the three bracketed terms by the size of the pasture area, A_x, converts equation (3) into the monthly net rate of change in energy for the entire dairy farm.

The portion of the herd not on pasture ($H_m - S_m A$) is fed a per capita allotment of concentrates or supplements (e.g., ready-mixed feeds, hay, or grain), X_e (MJ/hd) [equation (4)]. Our representative dairy purchases supplemental hay and barley [kilograms dry matter/head (kg DM/hd)]. These supplements are converted into energy units by multiplying the quantity of hay (y_m) and barley (z_m) purchased monthly by their respective energy contents, ϕ_y and ϕ_z. The energy available from supplements is restricted by a constraint on excessive feeding of grains or grain-based supplements to reduce the potential of acidosis or other related problems (Kellaway and Porta). Moreover, the proportion of the herd on supplemental feed is limited to 50 animals, as the farm does not have the necessary facilities to handle a larger number.

The total supply of energy available to the dairy herd in any one period ($E_{S,m}$) equals the energy generated by pasture (E_m), purchased supplements ($E_{e,m}$), and the amount of conserved hay fed in m (CE_m), where the latter is weighted by γ to account for the reduction of energy due to the conservation process (MAFF) [equation (5)].

Pasture and Supplement Costs

The cost of sowing and maintaining and, where necessary, the cost of fodder conservation for each pasture (C_x) was based on typical operations in the region of study; adjustments were made for the preferred methods of the case-study farmer (Scott). The annual cost for forage sowing and maintenance over all pastures is specified as:

$$C_{P,t} = \sum_{x=1}^{4} C_x A_{x,t}. \tag{15}$$

The total cost of supplemental feed is equal to the portion of the herd not on pasture ($H_m - S_m A$), multiplied by the per capita cost of supplements ($P_{y,m} y_m + P_{z,m} z_m$), i.e.,

$$C_{E,m} = \left(H_m - S_m A\right)\left[P_{y,m} y_m + P_{z,m} z_m\right], \tag{16}$$

where $P_{y,m}$ and $P_{z,m}$ (\$/kg DM) represent the monthly unit costs of hay and barley, respectively.

The forages grown on the case-study farm do not have an opportunity cost, as the two forage crops—oats and forage sorghum—are varieties selected for feed quality and do not produce economically viable seed quantities. The dairy as it stands now is a net importer of alfalfa hay (Tozer 1993b); thus the opportunity cost of selling alfalfa would be negative. Also, the dairy farm does not have sufficient land or capital resources for changing production practices to undertake alternative enterprises if the price for fluid milk falls relative to these alternatives. The pasture and forage sowing costs are not a function of the stocking rate, as the farmer undertakes a regular four-year pasture/forage renewal and rotation that is independent of stocking rate.

The Milk Production Function

The milk production function (Y_m) measures the maximum amount of milk that can be produced in a month if all available feed is consumed. It is derived by assuming that energy supplied equals energy demanded in month m, and then substituting $E_{S,m}$ into equation (13):

$$Y_m = \left(E_{S,m} - (\eta_{NP,m} + \eta_{PL,m} + \eta_{PD,m})\right)/\tau. \tag{17}$$

Equation (17) holds that monthly milk yield cannot exceed the residual energy remaining after the nonlactating demands of the herd have been met, normalized by the energy content of a liter of milk (τ). Typically, the total milk yield will be less than the maximum (Y_m) because the farm may profitably conserve forage in m to feed the herd in future months when pasture forage is relatively scarce. It also may be profitable for the farmer to maintain a lower stocking rate than that which will consume all available feed in m, so that fresh feed is available in $m + 1$ and beyond.

The milk production function is a complete summary of the bioeconomic processes of the dairy system. The first term in equation (17), $E_{S,m}$, captures the forage and energy systems, and also depends upon lagged values of the control and state variables. The second term ($\eta_{NP,m} + \eta_{PL,m} + \eta_{PD,m}$) captures herd dynamics.

Milk Revenue

The monthly milk net revenue function is defined as follows:

$$\pi_{I,m}(S, X_e, H, E) = \left[(P_{Q,m} * 0.6) + (P_{M,m} * 0.4)\right] * Y_m(S, X_e, H, E) - C_{VC}, \tag{18}$$

where $P_{Q,m}$ and $P_{M,m}$ are the prices of market and manufacturing milk, respectively. The farmer is assumed to receive a blend price made up of 60% market and 40% manufacturing prices. This split most closely represents the current milk sales of the farm. The term C_{VC} represents the costs of maintaining the dairy shed, equipment, and the herd. All prices and costs are net of the levies, fees, and taxes that apply to each case. Labor costs, above operator's labor, were included when the herd size exceeded 100 cows because the operator determined this is the size of the herd one operator could handle without hiring extra labor.

Analysis

We now apply the pasture-based dairy model to analyze the profitability of low-input diary systems over a wide range of circumstances. There is no unique low-input dairy system. These systems are generally pasture-based, but vary according to the extent that the producer relies on other feed sources to design a complete herd feeding management strategy. Consequently, we analyze the three feed management strategies

Table 1. Policy and Feed Management Scenarios Analyzed

Scenario	Pasture	Hay	Supplements	Deregulation	Price Premium	Net Present Value ($AUS)
1	Y	N	N	Partial	Y	73,327
2	Y	Y	N	Partial	Y	282,334
3	Y	Y	Y	Partial	Y	317,277
4	Y	N	N	Total	N	19,305
5	Y	Y	N	Total	N	26,030
6	Y	Y	Y	Total	N	26,030

of increasing flexibility: (*a*) a pure grazing-based operation with no fodder conservation (i.e., "extremely low-input" system); (*b*) an operation where some excess feed is conserved and fed in periods of low energy availability (i.e., "contemporary low-input" system); and (*c*) an operation where some proportion of the total herd is fed supplements (i.e., "conventional pasture/supplement" system).

We analyze these versions of low-input dairy systems for how well they perform under two policy regimes—either of which producers in the model farm area will potentially face (MacAulay): (*a*) partial deregulation, where the dairy farmer receives a blend price for milk assuming a price premium still exists for market milk; and (*b*) total deregulation, where the producer receives only the manufacturing price for all milk supplied. The impacts of these two potential policies on producer incomes will differ because the price premium for market milk is fairly substantial, and for some producers it may be economically infeasible to produce milk without receiving this premium. The six policy and feed management scenarios we analyze (three under each of the two regimes identified above) are summarized in table 1.

Parameter Values

Table 2 reports values for the age-specific parameters appearing in the model along with their sources. Forage-specific growth parameter values are shown in table 3. Table 4 presents values for a number of nonspecific parameters.

The cow beef price, P_b, appearing in livestock revenue equation (8), was calculated as the solution to a nonhomogeneous first-order difference equation:

$$P_b = 18.4742 * (0.8955)^{12(m+t)} + 78.0258, \tag{19}$$

using data provided by Tapner.

Price expectation equations also were derived for the monthly on-farm purchase price of hay ($P_{y,m}$) and barley ($P_{z,m}$) [equation (16)] as solutions to nonhomogeneous first-order difference equations:

Table 2. Age Class-Specific Parameters

Parameters	Description	Age Class (j)			
		2	3	4	5
(1) $\delta_{j,c}$	Culling rate (%)	0.15	0.05	0.05	0.95
(2) W_j	Weight of cow (kg)	500	535	570	600

Sources for parameters: (1) Tozer (1993b); (2) Holstein Friesian Association of Australia.

Table 3. Forage-Specific Growth Parameters

Month	Alfalfa [a]		Alfalfa, Ryegrass, and White Clover [b]		Forage Sorghum [c]		Forage Oats [d]	
	$a_{1,m}$	$b_{1,m}$	$a_{2,m}$	$b_{2,m}$	$a_{3,m}$	$b_{3,m}$	$a_{4,m}$	$b_{4,m}$
1	0.2958	0.0000016	0.2727	0.0000012				
2	0.4639	0.0000026	0.3063	0.0000014	0.7309	0.0000045		
3	0.6992	0.0000038	0.4070	0.0000019	0.6866	0.0000042		
4	0.6387	0.0000035	0.4275	0.0000019	0.6866	0.0000042		
5	0.5244	0.0000029	0.3723	0.0000017	0.2658	0.0000017		
6	0.3900	0.0000021	0.3796	0.0000017	0.0664	0.0000005		
7	0.2286	0.0000013	0.3606	0.0000016				
8	0.1412	0.0000008	0.2863	0.0000013			0.6102	0.0000120
9	0.0808	0.0000004	0.1785	0.0000008			0.6305	0.0000124
10	0.0672	0.0000004	0.1164	0.0000005			0.7356	0.0000145
11	0.1076	0.0000006	0.2182	0.0000010			0.9153	0.0000180
12	0.1346	0.0000007	0.1579	0.0000007			0.4729	0.0000093

[a] Derived from Doggett; Griffiths; Muldoon (1986b).
[b] Derived from Griffiths.
[c] Derived from Benson; Doggett.
[d] Derived from Griffiths; Muldoon (1986a).

$$P_{y,m} = 109.2196 * (0.5613)^{12(m+t)} + 126.8954 \tag{20}$$

and

$$P_{z,m} = 104.1571 * (0.5753)^{12(m+t)} + 96.1829, \tag{21}$$

using average monthly prices over the period July 1995 through June 1997 (*The Land*, 1995–97a, b).

The market milk price expectation appearing in equation (18) was estimated as follows:

Table 4. Nonspecific Parameters

Parameter	Description	Value(s) and Units
E_0	Initial pasture energy	209,017 (MJ)
H_0	Initial herd size	21,[a] 22,[b] 50,[c] 72,[d] 100[e] (hd)
δ_d	Death rate	0.05 (%)[f]
α_c	Annual calving rate	0.96 (%)[f]
$\delta_{0,c}$	Heifer calf culling rate	0.50 (%)[f]
γ	Energy reduction weight	0.90 (%)[g]
τ	Milk energy content	4.9454 (MJ/liter)[h]
ϕ_y	Energy content of hay	8.2 (MJ/kg DM)[g]
ϕ_z	Energy content of barley	13.7 (MJ/kg DM)[g]
$P_{M,m}$	Manufacturing milk price	21.672–31.256 (¢/liter)[f]
P_{bc}	Bull calf price	$AUS 30/hd[f]
P_{hc}	Heifer calf price	$AUS 25/hd[f]

[a] Initial herd size in Scenario 6.
[b] Initial herd size in Scenario 1.
[c] Initial herd size in Scenario 2.
[d] Initial herd size in Scenario 5.
[e] Initial herd size in Scenarios 3 and 4.
[f] Derived from Tozer (1998).
[g] Derived from Ministry of Agriculture, Fisheries, and Food (MAFF).
[h] Adapted from MAFF based on average milk composition.

$$P_{Q,m} = 0.015 * (0.9666)^{12(m+t)} + 41.865, \tag{22}$$

using data from the *Dairy Industry Statistics Handbook* (NSWDC). The price for manufacturing milk was derived from the current prices paid for this milk based on the composition of the milk in each month of the production year (Tozer 1998).

The model was solved using GAMS/MINOS on a Pentium 120 personal computer covering a 21-year time span. The first 10 years allow the transitory responses to the initial conditions for herd dynamics and pasture growth to stabilize.

Results

Scenario 1 (Partial Deregulation—Pasture). When cows are fed entirely on pasture, the herd size is equal to the optimal pasture stocking rate multiplied by the area of the farm. The optimal stocking rate is limited by the lowest monthly amount of energy produced over the planning horizon. This is demonstrated in figure 1, which graphs the energy supplied by pasture (the cyclical curve) and the energy demanded by the optimal herd size each month (the monotonic curve). Implicit in the figure is the interplay of two

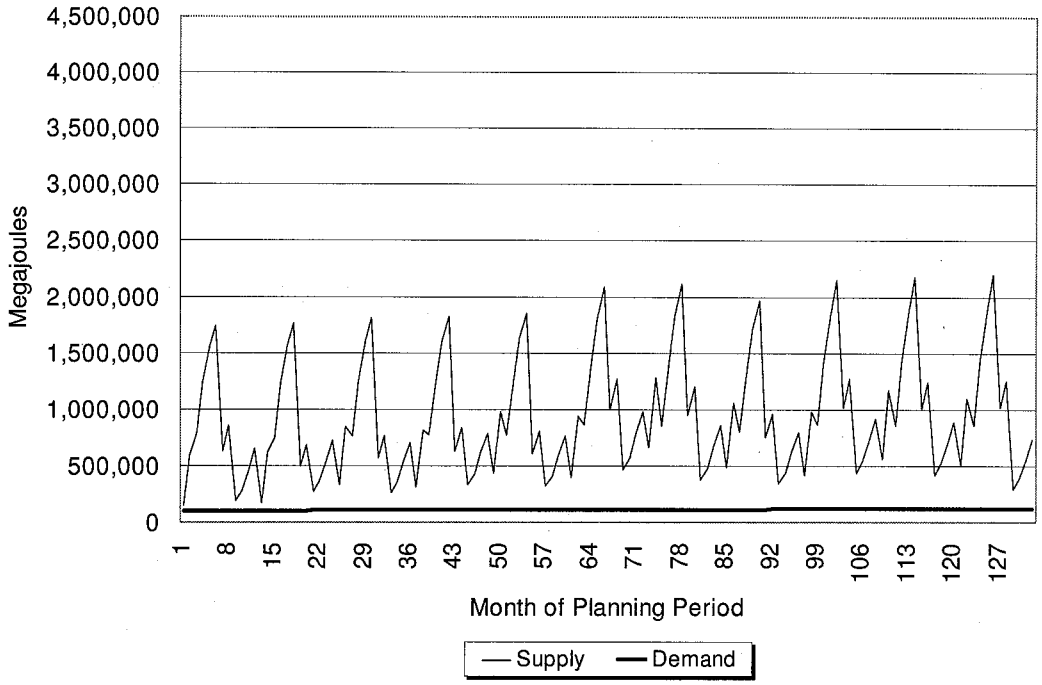

Figure 1. Energy demand and supply, Scenario 1

factors. First, the optimal program requires that the energy demanded by the herd not exceed the energy supplied by the pasture in any month [equation (6)]. This constraint is binding in month 1. Second, the herd dynamics equation (2) restricts the model dairy from increasing the stocking rate so as to consume excess energy in those months when the constraint is not binding. In other words, even if supply exceeds demand in months after the energy constraint is binding, the biological principles regulating herd dynamics prohibit the dairy from increasing the stocking rate sufficiently rapidly to utilize the excess forage. Consequently, the optimal stocking rate (0.6 cows/hectare) and the profitability of Scenario 1 are limited by the three months in which energy supplied exactly equals energy demanded. The net present value (NPV) generated from Scenario 1 is $AUS 73,327.

Scenario 2 (Partial Deregulation—Pasture and Hay). This scenario allows the dairy to conserve excess forage as hay which is fed to the herd in months when fresh forage production is low. We relied on the results from Scenario 1 to determine when pasture energy was limiting, and thus when to feed conserved hay. Figure 2 graphs the energy supply and demand for Scenario 2. Feeding conserved hay in low forage production months allows the dairy to increase the sustained stocking rate up to approximately 1.6 cows/hectare because the energy constraint (6) is binding for six months between months 36 and 80 at a higher level of energy production than in Scenario 1. The added flexibility of feeding conserved hay results in an NPV of $AUS 282,334—a 285% increase over the NPV in Scenario 1.

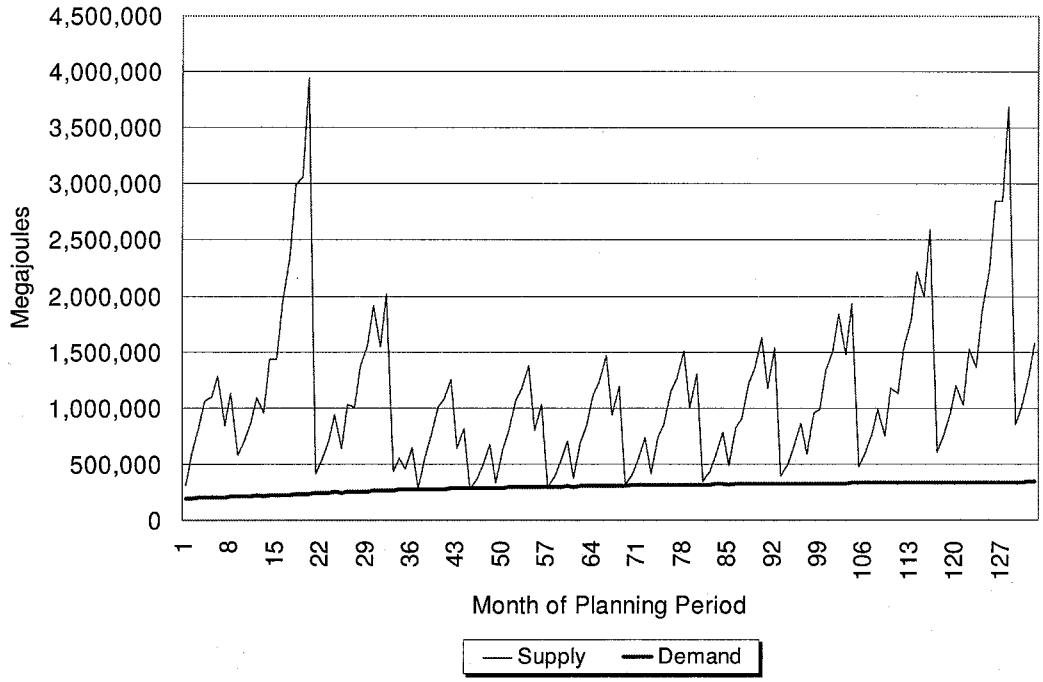

Figure 2. Energy demand and supply, Scenario 2

Scenario 3 (*Partial Deregulation—Pasture, Hay, and Supplements*). By purchasing supplements, the dairy farmer has access to an alternative energy supply that is not constrained by the biological processes regulating pasture production and herd dynamics. The optimal demand for and supply of pasture energy remain as in Scenario 2. However, the addition of supplemental feeding allows the farmer to increase the initial herd size by 50 cows. Sustaining larger increases is infeasible due to problems with acidosis and a limited area in the model farm for feeding cows. The NPV, at $AUS 317,277, is 12% higher than in Scenario 2.

Scenario 4 (*Total Deregulation—Pasture*). As in Scenario 1, when cows are fed entirely on pasture, the stocking rate is limited by the month yielding the lowest amount of pasture energy. The stocking rate is slightly lower than in the partial deregulation case, and the reduction in NPV to $AUS 19,305 can be attributed primarily to the price differential between market and manufacturing milk.

Scenario 5 (*Total Deregulation—Pasture and Hay*). The results for Scenario 5 are substantially different from the pasture-and-hay feed management strategy under partial deregulation. The stocking rate is reduced by 62.5% to 0.6 cows/ha and is not constrained by the supply of pasture energy in any month (figure 3). The limiting factor is the low price of manufacturing milk. The NPV for this combination of prices and management strategies is $AUS 26,030.

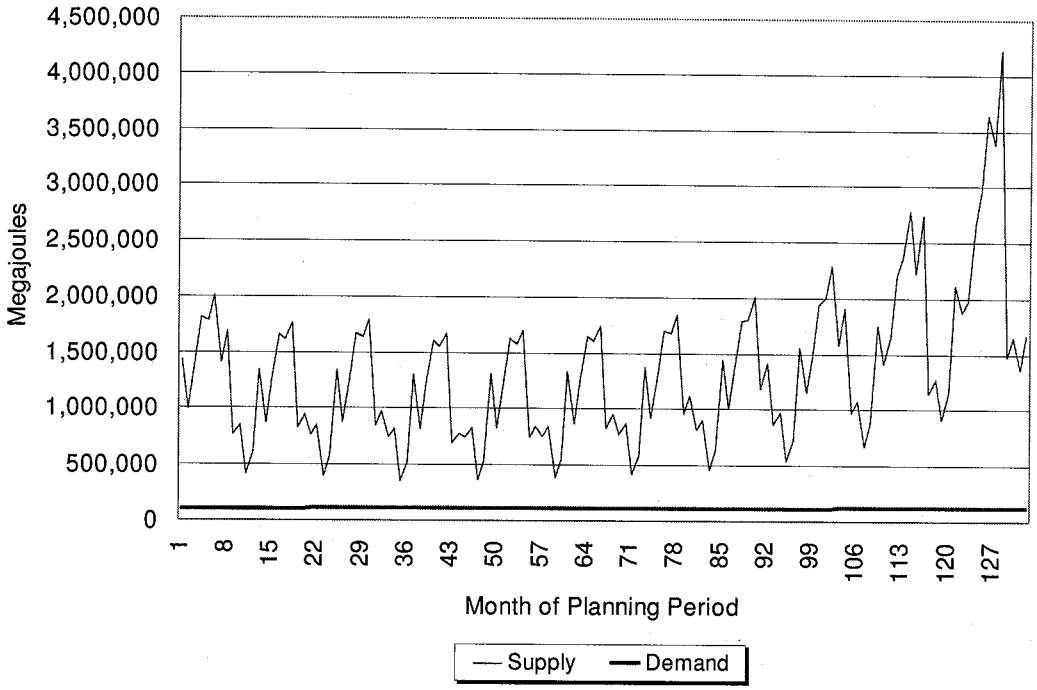

Figure 3. Energy demand and supply, Scenario 5

Scenario 6 (Total Deregulation—Pasture, Hay, and Supplements). The results for this scenario are identical to those in Scenario 5, since feeding cows supplements to produce milk at manufacturing milk prices is unprofitable.

Discussion and Concluding Comments

The increasing anecdotal evidence in dairy management trade journals that low-input dairying can be profitable under certain circumstances motivates this study. While there is no unique version of a low-input system in the literature, one can safely state that all such systems rely to varying extents on pasture to meet the energy requirements of the dairy herd. The least flexible of these systems relies on pasture to meet all of the herd's feeding needs. A moderately flexible system includes feeding conserved hay cut in periods when pasture production is high. The most flexible system includes feeding purchased supplements. We apply a novel pasture-based dairy model to frame six scenarios comparing the bioeconomic performance of the low, moderate, and high flexibility systems under two milk pricing regimes potentially faced by a representative Australian producer in New South Wales.

The scenarios reveal that the performance of pasture-based dairy systems depends on the complex interaction between potentially limiting biological and economic factors. Limiting biological factors include pasture production and the rate at which the herd progresses through various age and productive classes. The number of cows that the

farmer can reliably graze on pasture over the planning horizon without any supplemental feeding is restricted by the minimum amounts of pasture forage produced in the least productive months. The reason for this is that herd dynamics render infeasible the monthly stocking adjustments that would be needed to take profitable advantage of the peaks of the seasonal forage production cycle.

A producer can overcome these biological limitations to increased pasture stocking rates and herd sizes by feeding conserved hay cut during the peaks of the forage cycle, and/or by feeding purchased supplements. However, these supplemental feeding adjustments are costly, and their adoption may be limited by economic factors such as the price of milk. The blend price for milk received by producers under the partial deregulation policy (Scenarios 1–3) is sufficiently large compared to these costs, so that the representative producer earns the highest return by utilizing both supplement feed sources (Scenario 3). Alternatively, the manufacturing milk price received by producers under the total deregulation policy (Scenarios 4–6) is sufficiently low such that it is not cost effective for the representative producer to utilize the additional feeding flexibility offered by purchased supplements (Scenario 6). The representative producer's best response to total deregulation appears to be a highly productive pasture combined with the feeding of conserved hay.

While no single study can completely answer the question of which low-input system will perform the best in a given application, our research implies a number of general results that should be of use to producers in making a more informed selection. First, the bioeconomic conditions most favoring an entirely pasture-based system are a forage production cycle with highly productive seasonal periods, and/or a milk price that does not justify the costs of hay cutting or purchased supplements. Second, the conditions most favoring the addition of supplemental hay cutting are a forage production cycle whose seasonal peaks are large relative to low level troughs, and/or a milk price that makes it cost effective to cut hay but not to purchase supplements. Finally, the conditions most favoring a low-input system which combines pasture, hay cutting, and purchased supplements are a forage production cycle with low seasonal peaks and troughs, and/or a milk price sufficiently large to justify the costs of supplemental feeding adjustments.

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