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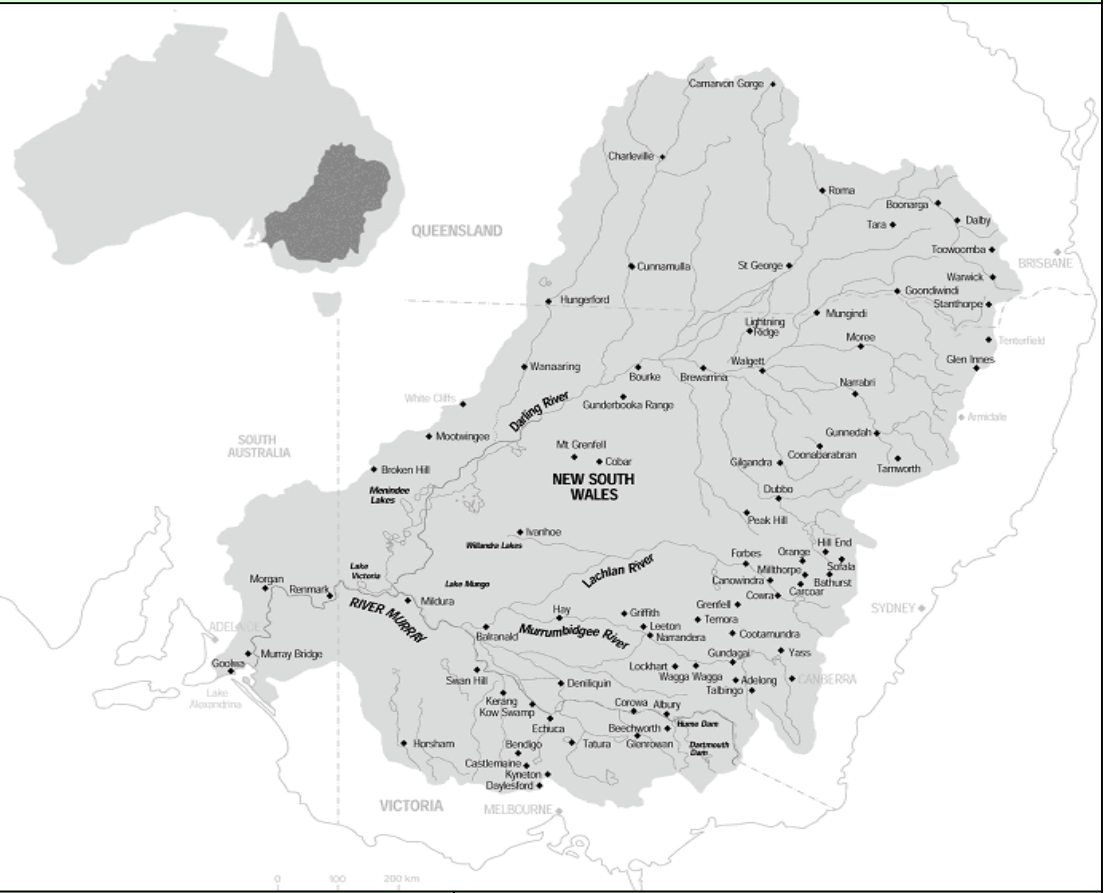

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Choosing the best forage species for a dairy farm – The Whole-farm approach

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Abbreviation key: LP = linear program,

ABSTRACT
Although a handful of forage species such as perennial ryegrass are predominant, there are a wide range of forage species that can be grown in sub tropical and temperate regions in Australia as dairy pastures. These species have differing seasonal yields, nutrient quality and water use efficiency characteristics, as demonstrated in a large study evaluating 30 species University of Sydney in New South Wales, Australia. Some species can be grazed, while others require mechanical harvesting that incurs a further cost. Previous comparisons of species that relied on yields of dry matter per unit of some input (typically land or water) cannot simultaneously take into account the season in which forage is produced, or other factors related to the costs of production and delivery to the cows. To effectively compare the profitability of individual species, or combinations of species, requires the use of a whole-farm model. Linear programming was used to find the most profitable mix of forage species for an irrigated dairy farm in an irrigation region of New South Wales, Australia. It was concluded that a typical farmer facing the prevailing milk and purchased feed prices with average milk production per cow would find a mix of species including large proportions of perennial ryegrass (*Lolium perenne*) and prairie grass (*Bromus willdenowii*) was most profitable. The result was robust to changes in seasonal milk pricing and moving from year round to seasonal calving patterns.

INTRODUCTION

The dairy regions in Australia spread from sub-tropical to Mediterranean and temperate climates, and so there are many forage species that could potentially be grown as forages for dairy production. Currently, perennial (*Lolium perenne*) and annual ryegrasses (*L. multiflorum*) are the dominant forage grazed by dairy cows on the majority of Australian dairy farms, particularly in southern (temperate) Australia. This is because of the relative ease of management, its high quality, and ability to grow for most of the year. On many farms other forage species are sown with ryegrass (white clover, *Trifolium repens*), provide feed when perennial ryegrass is not in production (e.g. kikuyu, *Pennisetum clandistinum*), or are harvested mechanically (e.g. maize).

The appropriate species to select, and in what proportion they should be grown, is a complex problem. Historically, selection between species and in particularly between varieties of a species has been biased towards the consideration of dry matter production (McMeekan, 1956). It has been shown that for many farms energy is the most common constraint to milk production (Fulkerson, 2000). Thus, the quality of feed is most appropriately measured by metabolisable energy and this has become an important criterion for farmers and farm advisors when selecting forage species. Another criterion of increasing importance given the trend towards increasing water prices, is the water use efficiency of forage species (Neal, 2005). There are a range of other aspects to take into account when choosing forage species, including nutrient content (e.g. protein and fibre), temporal aspects (i.e. when does the forage production occur) and harvesting aspects (i.e. can it be grazed or does it require mechanical harvesting).

To effectively choose a mix of forages that meets the farmer's objectives can be addressed through a farm system approach. In this paper, a linear programming model of a dairy farm was designed to maximise the profit for a farmer by choosing a mix of forage species and supplements to feed the dairy cattle. Data on forage yields and quality were determined from trial data (Neal, 2005). The model of cow nutritional requirements was based on the work underlying the CAMDAIRY computer model (Hulme, Kellaway and Booth, 1986).

The aims of this paper were to determine:

- The profit maximising mix of forages for a farm that calves year-round at flat milk prices, located in a similar area to where the study was undertaken and irrigation water could be purchased.
- The impact of using alternative criteria for choosing forages.
- The impact of progressively removing the most profitable forage species from the available options.
- The impact of seasonal calving and seasonal milk prices on the optimal forage mix.

MODEL DESCRIPTION

Modelling approach

A linear programming (LP) format was chosen to ensure that the best use of all inputs (e.g. land, forages and labour) were optimised for each modelled scenario. For example, specifying that a certain area of a particular forage should be used may require other inputs to be altered to maximise the profit (McCall and Clark, 1999).

LP has previously been used in grazing-based dairy models, although they have tended to focus on different issues than forage choice with simpler approaches to nutrition. For example Olney and Kirk (1989) examined strategic issues for Western Australian dairy farms such as stocking rate, beef activities, hay production and grain usage. Batterham et al., (1993) examined the strategic issues facing NSW dairy farmers, including quota choice, pasture combinations and fodder conservation. Tozer (1998) also used LP to examine quota and calving pattern issues for NSW dairy farmers. Neal (1999) examined strategic options for NSW farmers given the expected removal of the quota system. McCall and Clark (1999) used a LP to examine grazing based dairy systems in the northeast of the United States and in New Zealand. Strategic issues of stocking rates, calving patterns and the proportion of area planted to crops and pastures were examined simultaneously with tactical options of nitrogen fertiliser use and feeding levels.

Linear programming requires the use of linear equations to model relationships. However, some important relationships were considered to be non-linear. For example, the diminishing marginal returns of milk production in response to increased energy intake. These relationships can be approximated by a series of linear segments.

The objective function was to maximise the profit before tax and interest expense for a dairy farm over a single year. Revenue came from milk sales, cull sales and leasing land. Expenses were categorised by their cost driver. These cost categories included cow costs (e.g. artificial insemination, herd recording, veterinary), forage establishment costs (e.g. seed), fertiliser costs, irrigation water costs, cost of making conserving feed, cost of feeding conserved feed, purchased feed cost and labour cost. The equation defining profit is given by:

$$Z = \sum_{s=1}^{12} \begin{pmatrix} MilkSales_s + CullSales_s + LeaseOut_s - CowCosts_s - ForageCosts_s - FertiliserCosts_s - IrrigationCosts_s \\ - MakingConservedCosts_s - FeedingConservedCosts_s - PurchasedFeedCosts_s - LabourCosts_s - FixedCosts_s \end{pmatrix}$$

$$= \sum_{s=1}^{12} \begin{pmatrix} \sum_{m=1}^{1} \left(30.R_m^{MilkPrice}.A_{m,s}^{MilkProduced}\right) + \sum_{c=1}^{12}\left(R^{Cull}/12.A_c^{CowsCalved}\right) + \left(R^{LeasePrice}.A^{AreaLeased}\right) - \sum_{c=1}^{12}(C_{c,s}^{CowCost}.A_{c,s}^{CowsCalved}) \\ - \sum_{f=1}^{20}\left(((C_{s,f}^{Establish}/D_f^{Rotation}) + (L_{s,f}^{Establish}/D_f^{Rotation}.C^{Tractor}) + (L^{Top}.D_{s,f}^{Top}.C^{Tractor}) + (L^{Fertiliser}.D_{s,f}^{Fertiliser}.C^{Tractor})).A_f^{AreaSown}\right) \\ - \sum_{e=1}^{2}\left(C_e^{Fertiliser}.A_e^{FertApplied}/12\right) - \sum_{f=1}^{20}\left(C^{Water}.D_{s,f}^{WaterReq}.A_f^{AreaSown}\right) - \sum_{h=1}^{2}\sum_{f=1}^{20}\left((C_{h,s,f}^{MakeConserve} + L_{h,s,f}^{MakeConserve}.C^{Tractor}).A_{s,f,h}^{MakeConserve}\right) \\ - \sum_{h=1}^{2}\sum_{c=1}^{12}\sum_{f=1}^{20}\left((C_h^{FeedConserve} + L_h^{FeedConserve}.C^{Tractor}).A_{s,c,f,h}^{ConserveFed}\right) - \sum_{g=1}^{12}\left(C_g^{PurchasedFeed}.A_{s,g}^{PurchasedFeed}\right) - \left(C^{Labour}.A_s^{LabourReq}\right) - C^{Fix} \end{pmatrix}$$

[1]

Where:

Z	=	annual profit before tax (dollars);
$R_m^{MilkPrice}$	=	revenue per litre of fat and protein adjusted milk in market *m* (dollars);
$A_{m,s}^{MilkProduced}$	=	volume of milk in market *m* in month *s* (litres per day);
R^{Cull}	=	cull revenue per cow calved for the year (dollars);
$A_c^{CowsCalved}$	=	the number of cows calved in month *c* of the year;
$R^{LeasePrice}$	=	revenue per hectare leased out (dollars);

$A^{AreaLeased}$ = area leased out (hectares);

$C_{c,s}^{CowCost}$ = cost per cow calved in month *c* during month *s* (dollars);

$C_{s,f}^{Establish}$ = Cost of establishing and maintaining a hectare of forage *f* in month *s* (dollars);

$D_{f}^{Rotation}$ = Years between establishment and subsequent replanting of forage *f*;

$L_{s,f}^{Establish}$ = Labour required to establish a hectare of forage *f* (dollars);

$C^{Tractor}$ = Cost per hour for use of a tractor (dollars);

L^{Top} = Labour required to top one hectare (hours);

$D_{s,f}^{Top}$ = Number of times topping is required for forage *f* in month *s*;

$L^{Fertiliser}$ = Labour required to fertilise one hectare (hours);

$A_{f}^{AreaSown}$ = Area sown to forage *f* (hectares);

$C_{e}^{Fertiliser}$ = Cost per tonne of fertiliser *e* (dollars);

$A_{e}^{FertApplied}$ = Amount of fertiliser *e* applied (dollars);

C^{Water} = Cost of buying and pumping one megalitre of water (dollars);

$D_{s,f}^{Water\,\mathrm{Re}\,q}$ = Water requirement of each forage *f* in month *s* (megalitres);

$C_{h,s,f}^{MakeConserve}$ = Cost to make one hectare of forage *f* into conserved feed *h* during month *s* (dollars);

$L_{h,s,f}^{MakeConserve}$ = Labour required to make one hectare of forage *f* into conserved feed *h* during month *s* (hours);

$A_{s,f,h}^{MakeConserve}$ = Volume of forage *f* made into conserved feed *h* during month *s* (tonnes dry matter);

$C_{h}^{FeedConserve}$ = Cost per tonne of dry matter to feed conserved feed *h* (dollars);

$L_{h}^{FeedConserve}$ = Labour required to feed one tonne of conserved feed *h* (hours);

$A_{s,c,f,h}^{ConserveFed}$ = Volume of conserved feed *h* made from forage *f* fed each day in month *s* to cows calved in month *c* (kg of dry matter);

$C_{g}^{PurchasedFeed}$ = Cost per tonne of as-fed purchased feed (dollars);

$A_{s,g}^{PurchasedFeed}$ = Volume of purchased feed *g* bought in period *s* (tonnes as-fed);

C^{Labour} = Cost of labour including on-costs per hour (dollars);

$A_{s}^{Labour\,\mathrm{Re}\,q}$ = Labour required in month *s* (hours);

C^{Fix} = Fixed costs per month *s*.

Area Allocation

The area of the farm was assumed to be 200 hectares (500 acres). The farm was able to be sown with 36 alternatives, consisting of 20 forages and 16 combinations of a winter and summer forage. Area could also be leased out to alternative uses at the rate of $375 per hectare. The equation summarising the allocation of area was:

$$\sum_{f=1}^{36}\left(A_{f}^{AreaSown}\right)+A^{AreaLeased}\leq 200 \quad [2]$$

Forage production and utilisation

Forage was produced in accordance with the data from the forage study after the yields were adjusted to yields expected under commercial farm conditions. In general the yields were reduced by 15-35%. The adjustment process is further described in the following section. Once forage was produced it could be grazed by cows or conserved as either hay or silage. Conservation was subject to a loss factor of 10% to account for losses when harvesting and feeding out under good management conditions (A. Kaiser, pers comm.). The equation relating consumption and utilisation was:

$$30.A_{s,c,f}^{ForageGrazed} + 1000/(1 - D^{ConservedLoss}).A_{s,f,h}^{MakeConserved} \leq D_{f,s}^{\Pr oduction}.A_{f}^{AreaSown} \qquad [3]$$

Where:

$A_{s,c,f}^{ForageGrazed}$	=	Volume of feed eaten each day by cows calved in month *c* during month *s* of forage *f* (kg dry matter);
$D^{ConservedLoss}$	=	The proportion of forage lost during the process of conservation and feeding out;
$D_{f,s}^{\Pr oduction}$	=	Production of dry matter from one hectare of forage *f* during month *s* (kg dry matter).

Conserved and purchased feed

Conserved feed could be fed out in any period. The model assumes that forage conserved in month t can be fed out in earlier months. This is similar to assuming that the stock of feed at the end of the year will be higher or the same as at the start of the year. The equation relating the stock of conserved feed to the conserved feed actually fed to cows was:

$$\sum_{c=1}^{12}\sum_{s=1}^{12}\left(30.A_{s,c,f,h}^{ConserveFed}\right) \leq \sum_{s=1}^{12}\left(1000.A_{s,f,h}^{MakeConserved}\right) \qquad [4]$$

Purchased feed could be fed in any month to any group of cows. The equation describing this relationship was:

$$\sum_{c=1}^{12}\sum_{r=1}^{3}\left(30.A_{s,c,g,r}^{PurchFed}\right) \leq 1000.D_{g}^{PercentDM}.A_{s,g}^{PurchasedFeed} \qquad [5]$$

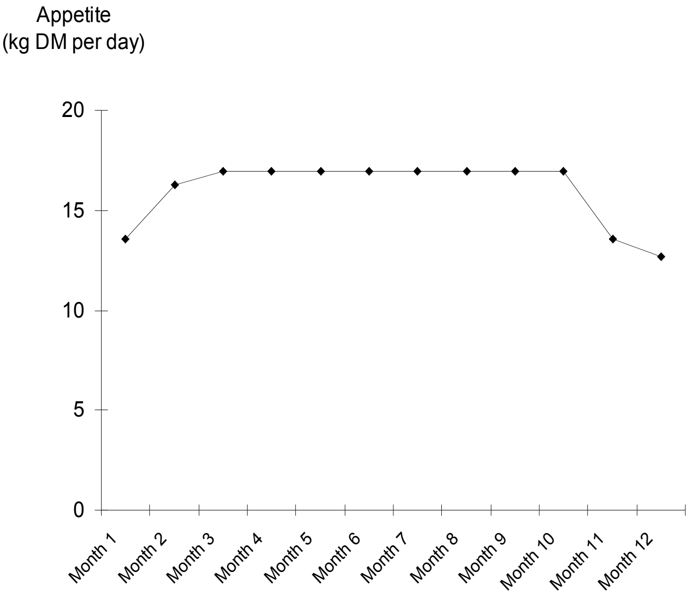
Where:

$A_{s,c,g,r}^{PurchFed}$	=	Volume of feed eaten each day by cows calved in month *c* during month *s* of purchased feed *g* at substitution level *r* (kg dry matter);
$D_{g}^{PercentDM}$	=	The percentage dry matter of feed *g*;
$A_{s,g}^{PurchasedFeed}$	=	Amount of feed *g* purchased in month *s* (t as-fed).

Nutrition – Dry matter

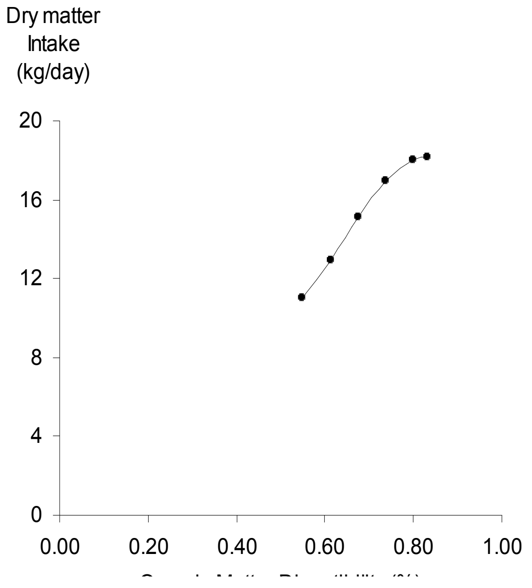
It was assumed that cows had a maximum level of appetite, although the actual amount of feed that could be eaten is adjusted for quality and substitution effects in a similar way to that proposed by Hulme, Kellaway and Booth (1986). The cow is assumed to eat 3.08% of bodyweight of good quality roughage per day. For an assumed weight of 550 kg, each cow would then eat a maximum of 16.94 kg DM per day. The maximum is lower for early lactation, being 80% of the maximum in the first month of lactation and 96% of the maximum for the second month of lactation (Vladiveloo and Holmes, 1979). Intake is also reduced during the dry period (Holmes et al., 2002). The dry matter intake for a cow calving at the start of month 1 and milking for 10 months is shown in figure 1.

Figure 1: Daily appetite for a cow in each month of lactation



Intake is adjusted for digestibility of the forages. Forages with organic matter (OM) digestibility of 74% are considered good quality roughage and would use one fill unit of intake, where a fill unit is the inverse of the CAMDAIRY concept of relative digestibility. Feed with OM digestibility lower than this reduce consumption in a linear relationship, with one kg DM of 55% OM digestibility feed using 1.54 fill units. Forages with OM digestibility higher than 74% increase consumption but at a diminishing rate. The relationship is shown in figure 2. Holmes et al. (2002) notes that intake increases with digestibility up to 80% but cautions the use of digestibility as a predictor of intake, citing other factors such as chop length and species differences. Alternative predictors such as NDF content (Mertens et al, 1997) have been found useful for some forages, but not legumes. While a more detailed intake model may have better predicted overall intake, it would also have become substantially more difficult to implement in the linear programming context.

Figure 2: Potential dry matter intake adjusted for digestibility



When feeding concentrates such as good quality grain, forage intake is reduced but overall intake increases. This is called the substitution effect, and the relationships of Moran and Trigg (1985) are used. When good quality concentrates make up less than 25% of the diet, each kilogram reduces forage intake by 0.64 fill units. When concentrates are between 25 and 50% of the diet, each marginal kilogram reduces forage intake by 0.84 fill units. For concentrate intakes over 50% of the diet, each marginal kilogram reduces forage intake by 1.22 fill units. Similarly to forage intake, the quality of concentrates is used to adjust the fill units and potential intake of the concentrate.

The cow may consume purchased feeds, forage by grazing or conserved feeds and this relationship, including quality adjustments and substitution is given by equation 6.

$$\sum_{g=1}^{12}\sum_{r=1}^{3}\left(D_{g,r}^{PurchFillUnits}.A_{s,c,g,r}^{PurchFed}\right)+\sum_{f=1}^{12}\left(D_{s,f}^{ForageFillUnits}.A_{s,c,f}^{ForageFed}\right)+\sum_{f=1}^{36}\sum_{h=1}^{3}\left(D_{h,f}^{ConserveFillUnits}.A_{s,c,f,h}^{ConserveFed}\right)\leq\left(D_{c,s}^{DMIntake}.A_{c}^{NumberCows}\right) \quad [6]$$

Where:

$D_{g,r}^{PurchFillUnits}$	=	The amount of appetite used by the consumption of one kg of DM of purchased feed *g* at substitution level *r* (kg DM);
$D_{s,f}^{ForageFillUnits}$	=	The amount of appetite used by the consumption of one kg of DM of forage *f* during month *s* (kg DM);
$D_{h,f}^{ConserveFillUnits}$	=	The amount of appetite used by the consumption of one kg of DM of conserved feed *h* made from forage *f* (kg DM);
$D_{c,s}^{DMIntake}$	=	The daily appetite of a cow calved in month *c* during month *s* for a feed with a fill unit value of 1 (kg DM).

A further constraint is required to ensure that the cow does not consume more then the prescribed percentage of concentrate at each substitution level. This is given by equation 7.

$$\sum_{g=1}^{12}\left(A_{s,c,g,r}^{PurchFed}\right)\leq\left(D_{r}^{Substitution}.D_{c,s}^{DMIntake}.A_{c}^{NumberCows}\right) \quad [7]$$

Where:

$D_{r}^{Substitution}$	=	The percentage of the diet at each substitution level *r* (kg DM).

Nutrition – Energy

Energy is supplied to the cows by the consumption of purchased feed, grazed forage, and conserved forage. The cows demand energy for maintenance and for milk production. Maintenance requirements include energy for maintenance of body weight as well as the additional requirements for pregnancy and changes in body condition. The ME values from NSW Agriculture (1997) were used in conjunction with an assumed pattern of body condition change related to stage of lactation. Cows were assumed to calve at body condition score (BCS) of 5.5 (on Earle's 8 point scale), reach a BCS of 4 in mid lactation and BCS 5 at dry off.

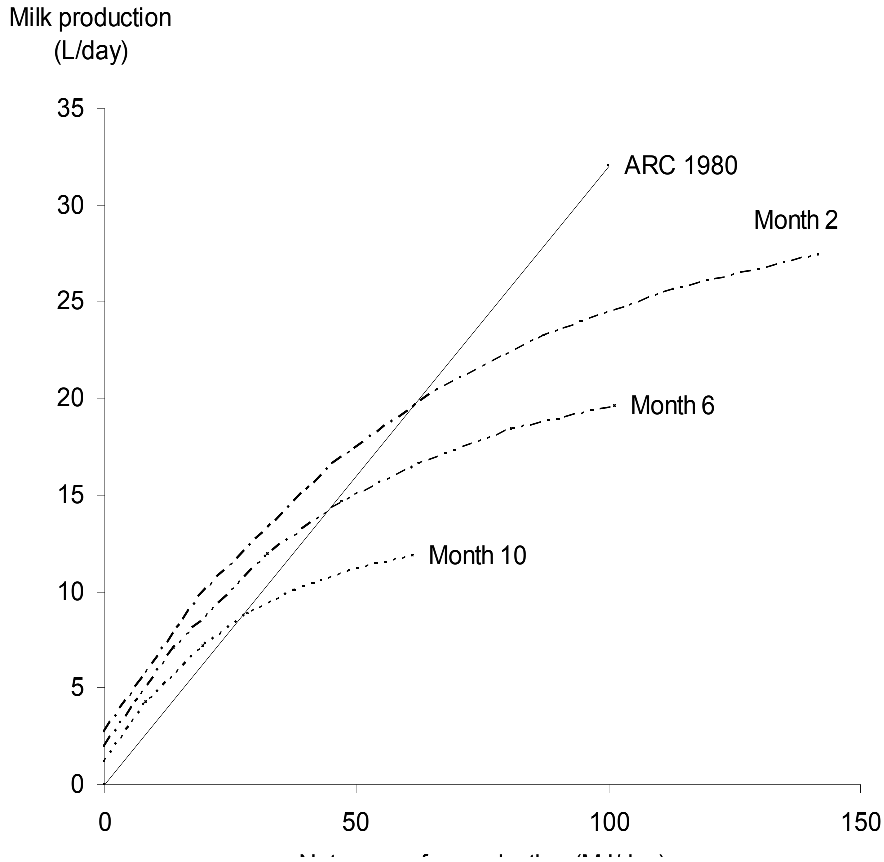
The equation for that ensures energy supply meets or exceeds energy demand is given in equation 8.

$$\sum_{g=1}^{12}\sum_{r=1}^{3}\left(D_{g,r}^{PurchME}.A_{s,c,g,r}^{PurchFed}\right)+\sum_{f=1}^{12}\left(D_{s,f}^{ForageME}.A_{s,c,f}^{ForageFed}\right)+\sum_{f=1}^{36}\sum_{h=1}^{3}\left(D_{h,f}^{ConserveME}.A_{s,c,f,h}^{ConserveFed}\right)\geq \left(D_{c,s}^{Ma\,int\,ME}.A_{c}^{NumberCows}\right)+\sum_{q=1}^{6}\left(D_{c,s,q}^{\Pr odME}.A_{c,s,q}^{Milk\,\Pr od}\right) \qquad [8]$$

$D_{g,r}^{PurchME}$	=	The metabolisable energy (ME) supplied by the consumption of one kg of DM of purchased feed *g* at substitution level *r* (MJ ME per kg DM);
$D_{s,f}^{ForageME}$	=	The metabolisable energy (ME) supplied by the consumption of one kg of DM of forage *f* during month *s* (MJ ME per kg DM);
$D_{h,f}^{ConserveME}$	=	The metabolisable energy (ME) supplied by the consumption of one kg of DM of conserved feed *h* made from forage *f* (MJ ME per kg DM);
$D_{c,s}^{Ma\,int\,ME}$	=	The daily ME requirement of a cow calved in month *c* during month *s* (MJ ME per cow).
$D_{c,s,q}^{\Pr odME}$	=	The ME requirement of a cow calved in month *c* during month *s* for the production of one litre of milk at the *q*th segment of the production function (MJ ME).
$A_{c,s,q}^{Milk\,\Pr od}$	=	The amount of milk produced by cows calved in month *c* during month *s* at the *q*th segment of the production function (litres).

In calculating energy required for production, it was considered important to represent the diminishing milk production with respect to energy intake. The linearization of the production function chosen by Hulme, Kellaway and Booth (1986) was implemented, giving six segments to approximate the production function. Figure 3 shows the production function for three different months of lactation and compares it to the response assumed by the fixed relationship suggested by ARC (1980).

Figure 3: Linearised production function at stages of lactation



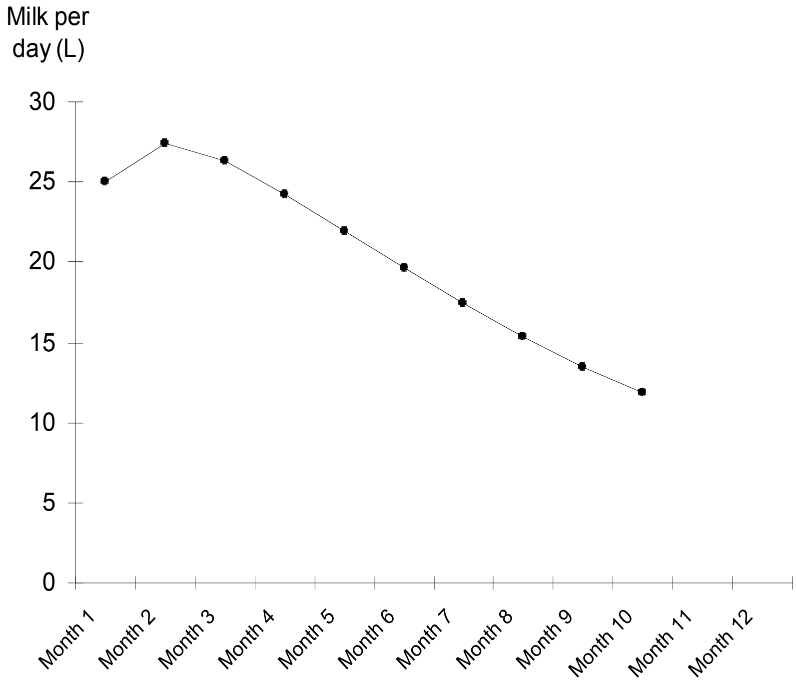
A restriction is required to ensure that production in each segment of the production function is below the maximum. This constraint is achieved through equation 9.

$$A_{c,s,q}^{Milk\,Prod} \leq \left(D_{c,s,q}^{Prod\,Restriction} . A_{c}^{NumberCows}\right) \qquad \textbf{[9]}$$

$D_{c,s,q}^{Prod\,Restriction}$ = The maximum amount of milk produced by a cow calved in month c during month s at the qth segment of the production function (litres).

The maximum daily milk production of a cow at each point in lactation can be found by using the lactation curve of Wood (1980). The model assumed the maximum daily production in each month was found by averaging the maximum daily production levels for each month, and is shown in figure 4.

Figure 4: Maximum daily milk production for a cow in each month of lactation



Nutrition – Protein

Protein needs were measured in terms of a minimum percentage of crude protein in the diet, varying through lactation and similar to those recommended by NSW Agriculture (1997). This was considered sufficient since energy is generally the most limiting nutrient in diets except where significant quantities of maize silage are fed. Protein could be supplied by purchased feed, grazed forage or conserved feed. The constraint ensuring the minimum crude protein requirements were met is in equation 9.

$$\sum_{g=1}^{12}\sum_{r=1}^{3}\left(D_{g}^{PurchCP}.A_{s,c,g,r}^{PurchFed}\right)+\sum_{f=1}^{12}\left(D_{s,f}^{ForageCP}.A_{s,c,f}^{ForageFed}\right)+\sum_{f=1}^{36}\sum_{h=1}^{3}\left(D_{h,f}^{ConserveCP}.A_{s,c,f,h}^{ConserveFed}\right)\geq\left(D_{c,s}^{CP\,Require}.D_{c,s}^{DMIntake}.A_{c}^{NumberCo}\right.$$

[10]

$D_{g}^{PurchCP}$	=	The crude protein (CP) percentage of purchased feed *g* (%CP);
$D_{s,f}^{ForageCP}$	=	The crude protein (CP) of forage *f* during month *s* (%CP);
$D_{h,f}^{ConserveCP}$	=	The crude protein (CP) of conserved feed *h* made from forage *f* (%CP);
$D_{c,s}^{CP\,Require}$	=	The minimum percentage CP requirement of a cow calved in month *c* during month *s* (%CP).

Nutrition – Fibre

The fibre in feeds were characterised by Neutral Detergent Fibre (NDF), with the cows requiring a minimum level of NDF of 30% of intake, similar to the levels recommended by NSW Agriculture (1997). Again, NDF could be supplied by purchased feed, grazed forage or conserved feed. The constraint ensuring the minimum NDF requirements were met is in equation 10.

$$\sum_{g=1}^{12}\sum_{r=1}^{3}\left(D_{g}^{PurchNDF}.A_{s,c,g,r}^{PurchFed}\right)+\sum_{f=1}^{12}\left(D_{s,f}^{ForageNDF}.A_{s,c,f}^{ForageFed}\right)+\sum_{f=1}^{36}\sum_{h=1}^{3}\left(D_{h,f}^{ConserveNDF}.A_{s,c,f,h}^{ConserveFed}\right)\geq\left(D^{NDF\,Require}.D_{c,s}^{DMIntake}.A_{c}^{Numbe}\right.$$

[11]

$D_{g}^{PurchNDF}$	=	The Neutral Detergent Fibre (NDF) percentage of purchased feed *g* (%NDF);
$D_{s,f}^{ForageNDF}$	=	The Neutral Detergent Fibre (NDF) of forage *f* during month *s* (%NDF);
$D_{h,f}^{ConserveNDF}$	=	The Neutral Detergent Fibre (NDF) of conserved feed *h* made from forage *f* (%NDF);
$D^{NDF\,Require}$	=	The minimum percentage NDF requirement of a cow calved in month *c* during month *s* (%NDF).

Fertiliser

Each forage was estimated as having a certain fertiliser requirement to grow the assumed yield. It was assumed that fertiliser was applied either through a single fertiliser of mixed nutrients or through the application of manure, and that these were good substitutes for each other. Manure production was related to the number of cows on the farm, and the fertiliser mix was purchased. The constraint ensuring fertiliser requirements were met is in equation 12.

$$\sum_{s=1}^{12}\sum_{f=1}^{12}\left(D_{s,f,e}^{ForageFert}.A_{f}^{AreaSown}\right)\leq\sum_{s=1}^{12}\sum_{c=1}^{12}\left(D_{s,c,e}^{ManureFert}.A_{c}^{NumberCows}\right)+\left(1000.A_{e}^{FertApplied}\right)\quad\textbf{[12]}$$

$D_{s,f,e}^{ForageFert}$	=	The requirement of forage *f* for fertiliser *e* during month *s* (kg);
$D_{s,c,e}^{ManureFert}$	=	The equivalent volume of fertiliser *e* produced by a cow calving in month *c* during month *s* (kg).

Labour

Many activities on the dairy farm require labour. These include forage establishment, topping to maintain pasture quality, fertiliser application, managing purchased feed, making conserved feed, feeding conserved feed, variable labour for milking cows, and fixed labour for maintenance and fencing. Labour could be supplied by owner labour or through the hire of labour. It was assumed that there was no unpaid labour, and so profit could be used to determine the return on assets, rather than the return to assets and management. The constraint ensuring labour requirements were met is in equation 13.

$$\sum_{f=1}^{20}\left(\left((L_{s,f}^{Establish}/D_{f}^{Rotation})+(L^{Top}.D_{s,f}^{Top})+(L^{Fertiliser}.D_{s,f}^{Fertiliser}.)\right).A_{f}^{AreaSown}\right)+\sum_{g=1}^{12}\left(L^{PurchasedFeed}.A_{s,g}^{PurchasedFeed}\right)$$
$$+\sum_{h=1}^{2}\sum_{f=1}^{20}\left(L_{h,s,f}^{MakeConserve}.A_{s,f,h}^{MakeConserve}\right)+\sum_{h=1}^{2}\sum_{c=1}^{12}\sum_{f=1}^{20}\left(L_{h}^{FeedConserve}.A_{s,c,f,h}^{ConserveFed}\right)$$
$$+\sum_{c=1}^{12}(L_{c,s}^{CowCost}.A_{c}^{NumberCows})+L^{Fix}\leq A_{s}^{Labour\,Req}+L^{OwnerLab}$$

[13]

$L^{PurchasedFeed}$	=	The labour required to handle each tonne of purchased feed (hours);
$L_{c,s}^{CowCost}$	=	The labour required for each cow calved in month *c* during month *s* (hours);
L^{Fix}	=	The amount of labour spent each month in fixed requirements (hours);
$A_{s}^{Labour\,Req}$	=	The labour required to be hired each month *s* (hours);
$L^{OwnerLab}$	=	The amount of unpaid labour supplied by an owner each month (hours).

Milk sales
Once milk was produced, it was assumed to be sold into the market at a price that could differ by months of the year. It was assume that only one market existed, although it would be relatively simple to allow for multiple markets and contracts which are now offered by some processors. The equation allowing milk to be sold is equation 14.

$$\sum_{m=1}^{1}\left(A_{s,m}^{MilkSold}\right) \le \sum_{q=1}^{6}\sum_{c=1}^{12}\left(A_{s,c,q}^{Milk\,Prod}\right) \qquad [14]$$

Calving patterns and stocking rates
Year-round production was assumed to occur, with equal numbers of cows calving in each month. This constraint is reflected in equation 15.

$$A_{c}^{NumberCows} = \sum_{c=1}^{12}\left(A_{c}^{NumberCows}\right)/12 \qquad [15]$$

It was assumed that there was a maximum stocking rate of 4 cows per hectare, so for the 200 hectare farm, no more than 800 cows could be calved during the year. This constraint is shown by equation 16.

$$\sum_{c=1}^{12}\left(A_{c}^{NumberCows}\right) \le 800 \qquad [16]$$

Farm Assets
Values for the farm assets were required to determine the return on assets. Assuming a level of appreciation (or depreciation) for different classes allowed the change in capital values (the capital return) to be calculated and added to the operating return in order to calculate an inclusive measure of return on assets. The total value of the farm was $4.6 million with net depreciation of 60,000, with asset classes detailed in table 1.

Table 1: Asset values and rate of appreciation

Asset Class	Value	Annual rate of appreciation	Appreciation
Land	2 000 000	5%	100 000
Rotary Dairy	800 000	-6%	-48 000
Sheds	100 000	-6%	-6 000
Plant and equipment	200 000	-20%	-40 000
Irrigation equipment	500 000	-10%	-50 000
Tractors	200 000	-20%	-40 000
Cows	800 000	3%	24 000
Total	**4 600 000**		**-60 000**

DATA AND ASSUMPTIONS

Data regarding plant yields and quality characteristics was gathered from the first two years of a trial carried out at Camden (150°39'E, 34°3'S), New South Wales (Neal, 2005). The field experiment was conducted on a on a clay alluvial soil (brown dermosol). The environment is regarded as a temperate environment, dominated by large summer rainfall events. During the summer, temperatures range from mean maximum temperature of 29.2 °C to mean minimum temperature of 15.1 °C. In winter the mean maximum temperature is 18.9 °C, while mean minimum is only 2.9 °C. The trial considered thirty species in all, although only 20 relatively successful species were considered in the model (table 2).

Table 2: Forage species grown alone

Abbrev.	Common name	Scientific name	Description
RS	Fodder radish	*Raphanu sativus*	Annual herb
RR	Rape	*Brassica rapa*	Annual herb
PE	Persian	*Triflium resupinatum*	Annual pasture legume
LA	Lab lab	*Lablab purpureus*	Legume crop
CH	Chicory	*Cachorium intybus*	Perennial herb
PL	Plantain	*Plantago lanceolata*	Perennial herb
LU	Lucerne	*Medicago sativa*	Perennial pasture legume
RE	Red clover	*Trifolium pratense*	Perennial pasture legume
WC	White clover	*Trifolium repens*	Perennial pasture legume
MA	Maize	*Zea mays*	Summer crop (C4)
SO	Sorghum	*Sorghum bicolor*	Summer crop (C4)
RB	Bi-annual ryegrass	*Lolium multiflorum*	Temperate annual grass
WH	Wheat	*Triticum aestivum*	Temperate annual grass
RA	Annual ryegrass	*Lolium multiflorum*	Temperate annual grass
FE	Fescue	*Festuca arundinacea*	Temperate perennial grass
PH	Phalaris	*Phalaris tuberosa*	Temperate perennial grass
PR	Prairie grass	*Bromus wildenowii*	Temperate perennial grass
RP	Perennial ryegrass	*Lolium perenne*	Temperate perennial grass
PA	Paspalum	*Paspalum dilatatum*	Tropical grass (C4)
KI	Kikuyu	*Pennisetum clandestinum*	Tropical grass (C4)

There were some combinations of species that were able to be grown, one after the other, on the same area within a year. The combinations considered feasible are listed in table 3 and were also included in the model.

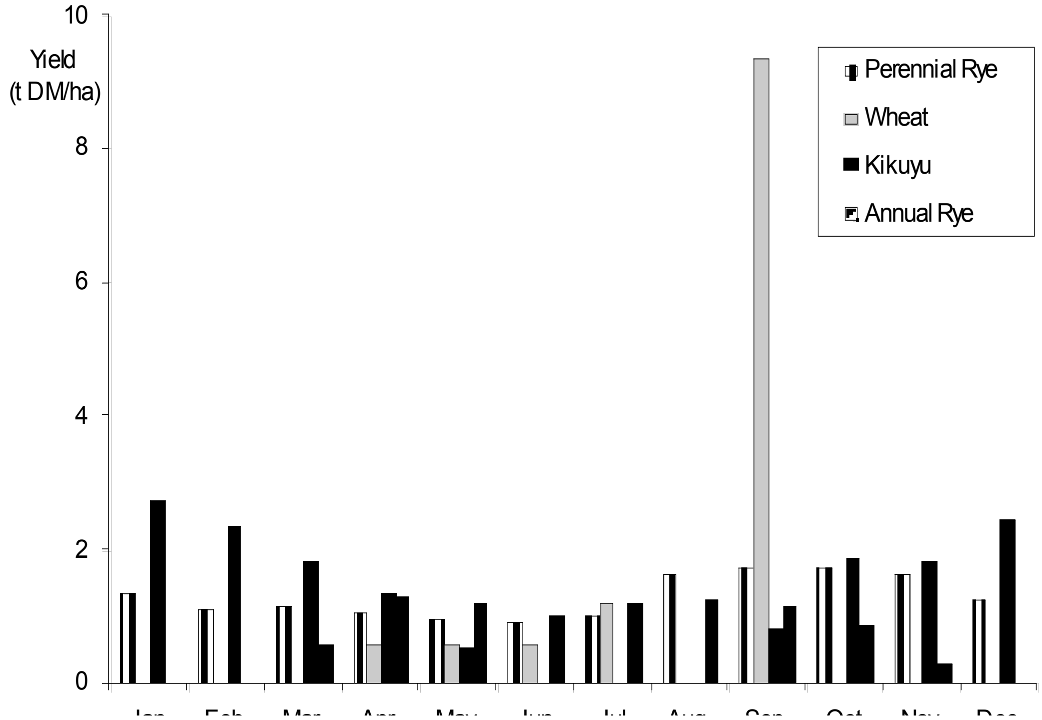
Table 3: Summer/Winter forage combinations

Abbrev.	Forage
MAxWH	Maize/Wheat
MAxRA	Maize/Annual ryegrass
MAxPE	Maize/Persian
MAxRR	Maize/Rape
SOxWH	Sorghum/Wheat
SOxRA	Sorghum/Annual ryegrass
SOxPE	Sorghum/Persian
SOxRR	Sorghum/Rape
KIxWH	Kikuyu/Wheat
KIxRA	Kikuyu/Annual ryegrass
KIxPE	Kikuyu/Persian
KIxRR	Kikuyu/Rape

LAxWH	Lab lab/Wheat
LAxRA	Lab lab/Annual ryegrass
LAxPE	Lab lab/Persian
LAxRR	Lab lab/Rape

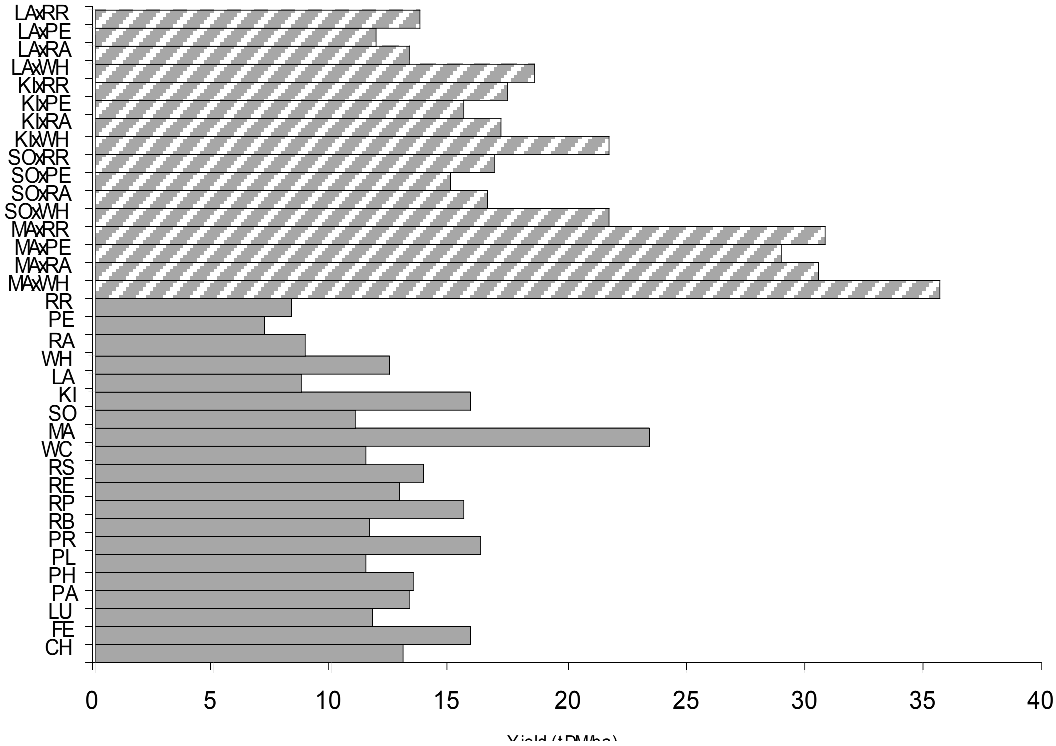
The seasonal distribution of the growth of these species differed markedly. For example, wheat produces one large harvest in September, following some grazings from April through to July. Kikuyu's production is concentrated heavily in the summer months, whereas annual ryegrass produces mainly in the winter months. Perennial ryegrass is far more consistent, producing dry matter throughout the year, though with differing quality (figure 4).

Figure 4: Seasonal distributions of selected forage species



The yields of grazed forages in the trial were adjusted downwards by 33% to take into account the utilisation achievable on a farm. The yields of harvested forages, such as maize, were reduced by 15%. Where combinations of species were considered in the model, the growing season for one or both forages were shorter than in the trial. In this case, adjustments were made to their yields. Figure 5 shows the adjusted yields of all forages and feasible combinations considered in the model.

Figure 5: Adjusted yield of forages and combinations of forages



Year-round calving system at flat milk prices

The basic model assumed that year-round calving was employed, with a uniform number of cows calving in each month through the year. The milk price was assumed to be uniform through the year, using a price of $0.33 per litre, similar to current prices (P. Neal, pers. Comm.).

Resources were priced at their current market value. Labour could be hired at a rate of $24 per hour throughout the year, which included tax, superannuation and workers compensation requirements. Fertiliser cost $505 per t for urea (46% nitrogen) and $360 per t for a blend (P 4.4: K 25.0: S 5.5). Water cost $45 per megalitre for the right to use it and $22 per megalitre for the electricity to pump it. Tractor running costs (fuel and oil plus repairs and maintenance) cost $12 per hour of operation (NSW DPI, 2006). The contract cost of harvesting wheat or maize into a pit for silage was $50 per t DM.

RESULTS AND DISCUSSION

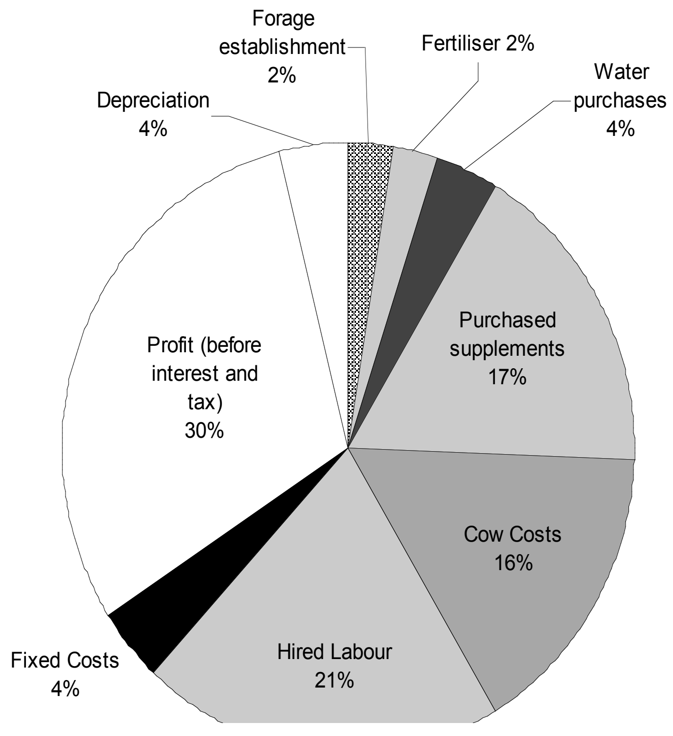
1. Optimal forage mix

The optimal forage mix was found by maximising the profit for the farmer. The optimal mix consisted mainly of 94 ha (56%) of prairie grass (PR) and 104 ha (23.5%) of perennial ryegrass. A small amount of a combination was also part of the optimal mix, with 2 ha of Kikuyu/Rape (KIxRR). No area was leased out, with a shadow price for land of $AUD $1,100/ha implying that it could be profitable to lease in extra land if the annual lease was available at less than this value.

The farm calved the maximum number of cows which was 800, and produced 4.1 million litre of milk for the year. On average, each cow produced 5,200 litres, or about 86% of their potential production. The farm operations did not involve any forage conservation, with a larger amount of purchased feed being used (1260 t DM). The purchased feed consisted mainly of barley grain (87%), with the remainder being maize grain and cereal straw.

Total revenue was $AUD 1.489 million, with milk sales accounting for 92% of revenue. Labour (almost 7 full time equivalents) accounted for 21% of revenue, with cow costs, bought supplement and fixed costs being the next most major cost categories. The resulting profit before interest and tax (but including changes in capital value) was $AUD 410 700, or equivalent to 8.9% return on assets (figure 6).

Figure 6: Costs and profit as a share of revenue



2. Alternative criterion for choosing forages

There are other criteria that could be used to choose forages rather than profit maximisation. As an example, farmers may have been advised to use forages that maximise dry matter yield. The logical conclusion from this objective is to plant the entire area to the maize/wheat combination, with the result that the return on assets falls to -0.4% (table 4). This is because the costs of harvesting and feeding out are expensive relative to grazing.

An improved criterion might have been to choose the forage that maximised yield from amongst the grazed forages, which was the kikuyu/rape combination. The return on assets from this criterion was 5.8%, less than two thirds of the profit maximising choice. The maximum energy density criterion would have lead to perennial ryegrass being chosen. This resulted in a return on assets similar to the optimum because the perennial ryegrass also had other favourable characteristics such as high yield and low costs of establishment.

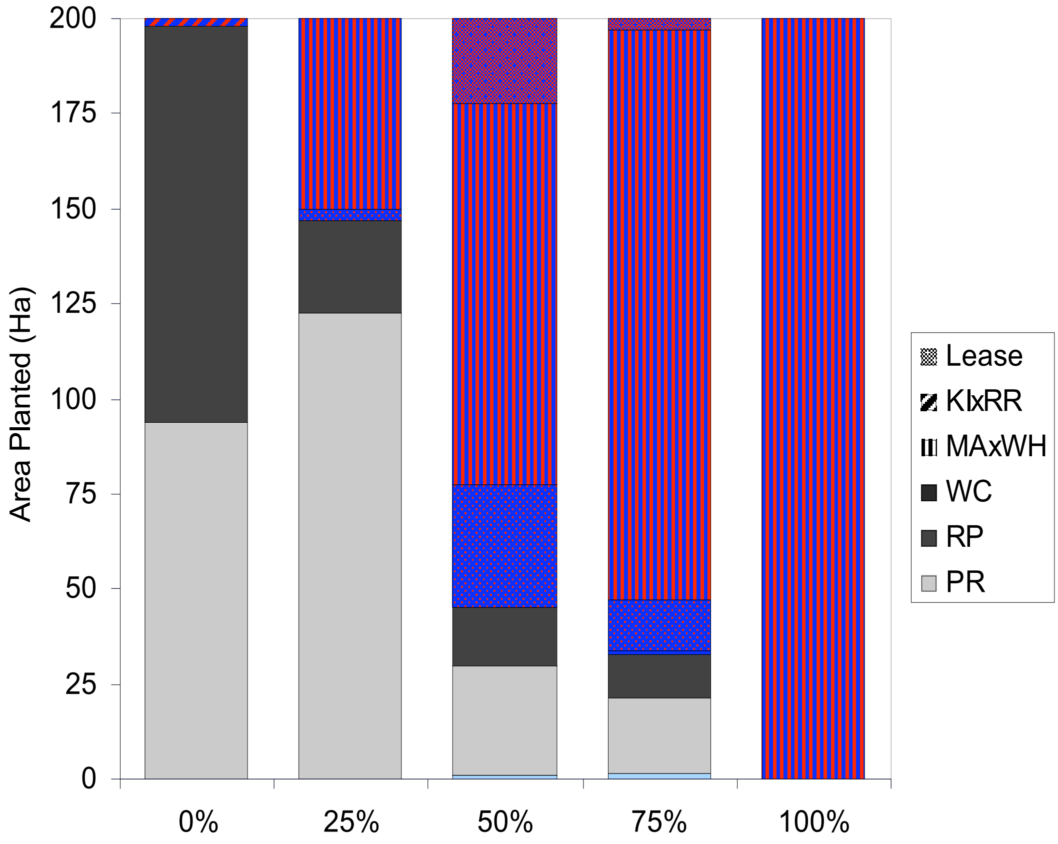
Choosing the forage with the highest water use efficiency would have resulted in maize being grown. However, because of the costs associated with harvesting and feeding out, the return on assets was quite low at 1%. In summary, alterative criteria will not maximise profit and may significantly reduce profit. Although the maximum energy density criterion led to near optimal profitability, this result would not be consistent in other situations.

Table 4: Forage area and return on assets associated with different criterion

Criteria for forage choice	Maximum profit	Maximum yield	Maximum yield - all grazed	Maximum energy density	Maximum water use efficiency
Forage Choice	Optimum	MAxWH	KIxRR	RP	MA
Forage area					
MAxWH		200			
KIxRR	2		200		
RP	104			200	
MA					200
PR	94				
Return on Assets					
	8.9%	-0.4%	5.8%	8.7%	1.0%

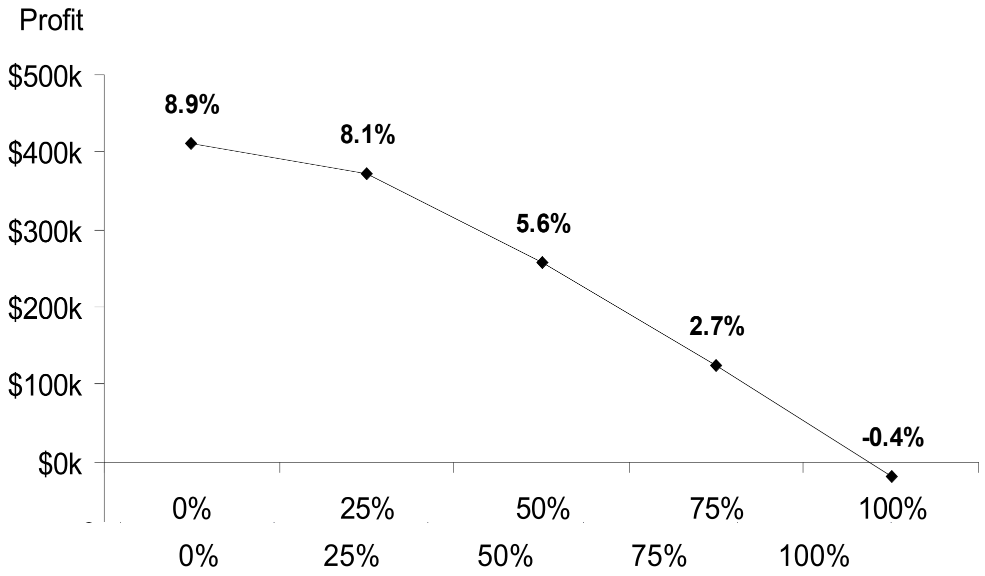
Assuming that the farmer does plant some percentage of the area to the maize/wheat combination, the best use for the remainder of the land can be found assuming that profit maximisation holds for other decisions. For example, if 25% of the land is used for the maize/wheat combination, increasing the area of prairie grass is the best response. Increasing the maize/wheat area to 50% of the farm results in some land being leased out to another use, with the remaining area mainly white clover and prairie grass. This pattern is continued when the maize/wheat area is forced to 75% of the farm (figure 7).

Figure 7: Use of land with an increasing area of maize/wheat combination



Introducing only a 25% area of maize/wheat leads to a small reduction in the return on assets (from 8.9% to 8.1%). This reduction is small because of the ease of substitution of other forages and purchased feed near the optimum. However, subsequent increases in the area of maize/wheat cause much larger decreases in the return on assets because of the diminishing marginal returns of substitutes. The impact on profit from increasing the area planted to the maize/wheat combination is shown in figure 8.

Figure 8: Profit and return on assets with increases in area planted to Maize/Wheat



3. Removing the most profitable forages

The optimal forage combination resulted in more than half the area being planted to perennial ryegrass, one of the most commonly used species. The best response of farmers who were not able or willing to use perennial ryegrass was tested by removing perennial ryegrass from the available options. The result was only a small reduction in profit to a return on assets from 8.9% to 8.8%, with increases in the area of prairie grass, the kikuyu/rape combination and other species. Further sensitivity analysis was performed by removing prairie grass, resulting in the introduction of a large area of red clover, the introduction of a maize/rape combination, as well as increases in the use of the Kikuyu/rape combination (table 5). Removing prairie led to a much more significant reduction in return on assets, from 8.8% to 7.8%.

Table 5: Response to removal of most profitable forages

	Base	No RP	No RP or PR
Forage Area			
RP	104		
PR	94	150	
KIxRR	2	34	59
RE			92
MAxRR			28
Other		16	21
Return on Assets			
	8.9%	8.8%	7.8%

4. Sensitivity:

Seasonal milk prices

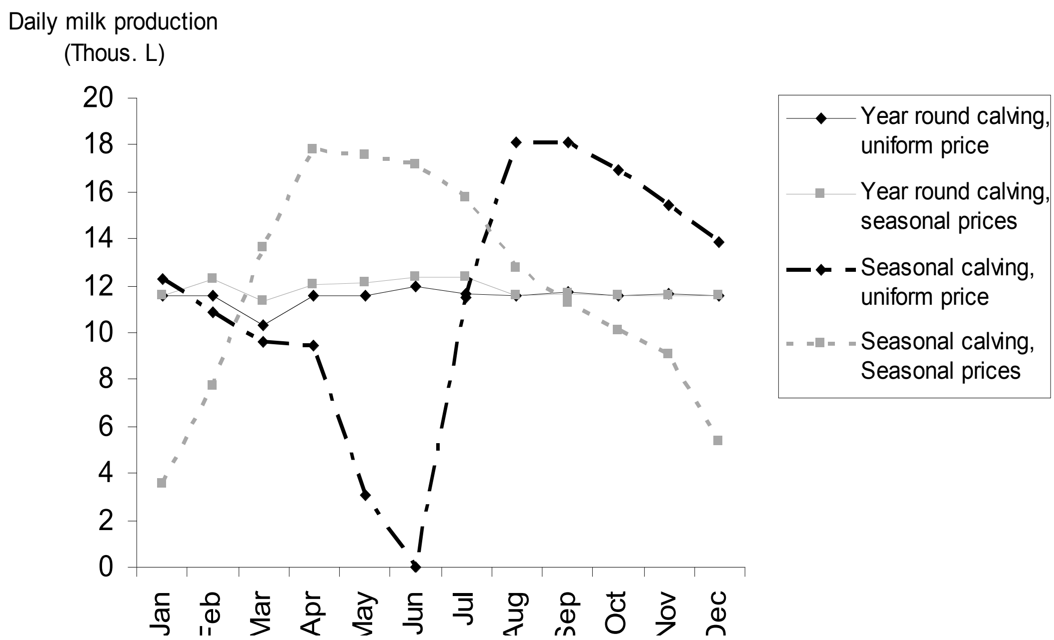
Processors can use different milk prices through the year to encourage production when it is more costly to produce milk, or reduce prices when it milk is relatively cheap to produce. In some areas of Australia a two price system operates with a higher price from February to July and a lower price August to January. The model was solved again with a seasonal two price system with a low price of $0.305 per L and a high price of $0.355, averaging the same $0.33 per litre as with the uniform milk price.

With the introduction of seasonal pricing, the major response in the model was to change 20 hectares from prairie to perennial ryegrass. Modest increases in milk production occurred during the months of the higher milk prices through higher levels of feeding per cow (figure 9). The return on assets increased from 8.9% to 9.0%.

Seasonal calving pattern
The base model was constrained by ensuring year round calving, a common practise in NSW. This constraint was relaxed, allowing cows to be calved in any month, although the maximum number of cows calved during the year was still limited to 800. The area planted to prairie grass increased by almost 20 hectares at the expense of the kikuyu/rape mix and the perennial ryegrass. Milk production became sharply peaked since all cows were calving in July and August (figure 9). The increase in return on assets was modest, going from 8.9% in the base case to 9.1%, implying that simply introducing seasonal calving was not highly profitable.

Seasonal milk prices and seasonal calving pattern
The model was then used to estimate the response under both seasonal prices and seasonal calving. The area planted to perennial ryegrass increased by 40 hectares. Milk production became highly peaked during the higher priced months, although calving was more spread out than the uniform pricing/year-round calving scenario, occurring in the months January to April. Return on assets increased to 9.4%, showing for farms in this area that the combination of seasonal calving and seasonal prices was more favourable than the other scenarios.

Figure 9: Effect on milk production of seasonal milk prices and seasonal calving



Water price
To model the sensitivity of the farm's decisions to the annual water price, it was doubled from $45 per megalitre (ML) in the base model to $90 /ML. If the farmer did not adjust their behaviour, profit would have fallen by $38,800, representing 9% of the base profit. This profit impact without adjustment was calculated as $45 /ML

multiplied by base water use of 862 ML. In the profit maximising solution there was only a modest change in the choice of species, with 20 ha moving from prairie to the kikuyu/rape combination. The impact on water use was a reduction of 5%, from 862 ML to 820 ML. The reduction in profit was $38,100, only a small improvement when compared with no adjustment to behaviour.

Conclusions

It was found to be most profitable to use a mix of forage species rather than choosing a single forage or combination of forages based on alternative criteria that did not maximise profit. It was also found that the optimum mix of species was not much more profitable than using one of the most common forage species, perennial ryegrass. Progressively removing prairie grass and perennial ryegrass from the available alternatives also did not cause large reductions in profit. It was also found that the ability to seasonally calve and adjust to seasonal milk prices did not make a large difference to overall profit or the mix of species, but it did affect the optimal calving pattern. The modest impact of increased water price on the model farm suggested that some farmers may not respond to increased prices with changes in forage areas. However, for farms that have less efficient technology (e.g. flood irrigation), a response such as investing in centre pivot irrigation could occur, subsequently affecting forage choice. Further, for farms that have a lower profit margin than the base farm, significant increases in water prices may result in a response where they exit the industry.

There were several limitations in the current study. First, risk in terms of price or production risk was not considered. This could be addressed by using a state based representation of uncertainty as suggested by Chambers and Quiggin (2000). Second, the model assumes each forage requires a certain level of water for a fixed production level, disallowing potential responses by altering irrigation levels. Data from the forage trial could be used to estimate the response of forage growth to additional (or reduced) irrigation. Third, the model does not currently model the ability to substitute capital for labour or other inputs. These possibilities could be incorporated with integer variables to represent the availability of capital items. Fourthly, technological changes, such as the availability of improvements in the genetic merit of cattle, were not included in the model. However, they could be incorporated in a similar way to capital items by using integer variables. Fifthly, the digestibility based intake model of the cow could be improved to increase the reliability of predictions. This may not be easily done in a LP model, but optima suggested by the LP model may be checked by using a more complex nutrition model (e.g. Cornell Model) or even tested in field trials with real animals. Finally, other limitations of the current work include the climatic region of applicability and the potential that farms with different objectives, constraints or managerial ability will have different optimal forage mixes.

Despite these limitations, it could be concluded that a mix of forages similar to the model's optimum will be profitable in locations comparable with those where the forage trial was carried out. Furthermore, in determining the optimal mix, emphasis should be placed on applying knowledge about the yield and nutritive characteristics of forages into a whole farm context, taking into account the costs of growing and feeding them, as well as the ability to substitute with other inputs such as purchased feeds, fertiliser, water, labour, and capital.

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