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Minimum Cost Feeding of Dairy Cows in Northern Victoria

by

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General Paper No. G-195 January 2010

ISSN 1 031 9034 ISBN 978 1 921654 02 2

Minimum cost feeding of dairy cows in northern Victoria

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Abstract

A new era of water scarcity has changed past patterns of feeding dairy cows in northern Victoria. This paper derives a model for estimating least-cost feeding of dairy cows under a range of assumptions regarding prices for irrigation water, hay and feed grain. The cost-minimisation is subject to a variety of nutritional constraints, including seasonal provision of energy, fibre and protein.

It is found that the optimal feeding regime varies considerable with input prices, from an irrigated pasture-based system to a diet based much more on bought-in hay and feed grain. This change broadly mimics that which has taken place in the region over the current extended period of drought.

Output from the linear programming model is used to estimate the CES substitution parameter between water and the other inputs. This parameter is estimated at 0.7, significantly higher than the 0.2 originally used.

JEL Classifications: C61; Q15; Q25

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1. Introduction

Dairy farming is an important industry in northern Victoria. Milk accounts for almost 30 per cent of the total value of agricultural products in Victoria, as opposed to more like 10 per cent for Australia as a whole (ABS 2009), while milk from the northern Victoria/southern New South Wales region accounts for almost 25 per cent of the national total.

The economical feeding of cows is a major component of dairy farmer decision making. Feed typically accounts for the lion's share of variable costs. For one farm in northern Victoria, Ho *et al.* (2006) found that feed costs were typically 60 per cent of farm variable costs, but this varied between 40 and 89 per cent over a 40-year period.

In the past, the feeding of cows in this region was based to a large extent on the irrigation of both annual and perennial pastures, necessary given the rainfall and evaporation characteristics of the region (Ho *et al.* 2007). In 2004–05, irrigation of pastures by the dairy industry accounted for over half of total irrigation water used in Victoria (ABS 2006).

Irrigation was enabled by abundant supplies of water; however, the past decade or so has seen rainfall much below average, and radically lower availability of water for irrigation. As water is now a tradable commodity, water scarcity is reflected in water market prices, which spike up considerably in years with limited water supply. In addition to market related increases in the price of water, there have also been cost increases related to access and use of the storage and distribution infrastructure (operated by Goulburn-Murray Water). When water is expensive, irrigating pastures can become a costly rather than a relatively cheap means of feeding dairy cattle.

Farmers can substitute away from water by buying in feed. However in drought years, other feed sources such as hay and feed grain are also likely to be expensive. In particular, the prices of hay and water are likely to be correlated (Ho *et al.* 2005). Grain is somewhat more independent as it is grown in different regions and may even be imported.

The economical feeding of dairy cows whilst also satisfying relatively complex nutritional requirements to maintain cow health and milk production is an interesting and relevant problem. Feed budgeting is relatively complex, and a number of manuals and software packages have been devised to assist dairy farmers (Jacobs and Hargreaves 2002).

Ho *et al.* (2007) look at ways to maintain profitability in the face of lower water availability (and hence higher water prices) on two case study farms in northern Victoria. For the first farm, options include purchasing more fodder or replacing some perennial pasture with annual pasture. The second farm had already made a large-scale conversion to annual pasture, so the options evaluated were a potential shift back into perennial pasture and/or using less fertiliser on the perennial pasture.

In other related work, a linear programming formulation was used by Tozer (2000) to model least-cost feeding of heifers while also aiming to reach 600 kg by calving.

This modelling develops a linear program to find the least-cost way to feed cows subject to a number of nutritional and physical constraints. The feed budget may be met from four types of feed inputs and must satisfy four basic nutritional constraints in each of four seasons. The aim is to assess how the optimal mix of feed types changes as relative prices change, to consider substitutability between inputs.

Although the modelling is devised for a single dairy cow (albeit considering both spring-calving and autumn-calving cows), the approach is very much regional as available resources and production coefficients reflect regional averages. Ho *et al.* (2005) emphasise that there is no right option for every dairy farmer, good options depend on the resources, goals and skills of individual farms. While this is no doubt true, we are not aiming to provide farm level advice, but rather, to look at resource allocation at a regional scale.

We have chosen cost minimisation (subject to a certain level of output (milk)) as the goal. In their evaluation, Ho *et al.* (2007) also assume constant milk production per cow (and constant cows per farm). However, other goals might have been considered, such as maximising output per cow (by increasing grain/concentrates fed for example) or maximising output per hectare (by increasing stocking rates and supplementary feeding, for example) (Kellaway and Harrington 2004; Tozer *et al.* 2003).

2. Minimum cost feeding

In this modelling, farmers can choose to feed cows via a mix of annual and perennial pastures, feed grain and hay, both brought-in and home-grown. In real life, there is a much more diverse set of possibilities, including silage, other home-grown forage crops, and other alternative feed sources like grape marc. Nevertheless, we have captured the most important items.

The aim is to provide sufficient energy each season, while also ensuring that the percentages of protein and fibre in the diet are above some minimum levels, which vary by season. In addition, since cows have a limited appetite, the feed must be sufficiently dense in energy. To summarise the advantages of the different feed types:

- pastures are an excellent food for cattle and satisfy all the nutritional constraints, however irrigation can be expensive if water is expensive. Dry matter production is limited if pastures are not irrigated.
- hay tends to be relatively cheap, can be rich in protein (though subject to significant variability) and particularly rich in fibre, but not dense enough in energy.
- feed grain can be relatively expensive. It is dense in energy, but lacks protein and fibre.

Irrigated annual pastures may be cut and conserved in spring, and fed out as hay over the rest of the year. It is assumed that dryland annual pastures and perennial pastures are not conserved. It is assumed that the quantity of hay produced is 85 per cent of the dry matter production for grazing, with the same energy, protein and fibre characteristics as the bought-in hay.

Annual pasture may produce more dry matter per ML than perennial pasture but costs associated with producing, conserving and feeding out can be relatively high. The more expensive water is, the more likely the costs of conserving and feeding out annual pastures are to be outweighed by extra water costs of perennial pastures. The efficiency of annual pastures depends on how much is being grazed directly and how much is being conserved for later in the year.

The use of grain in dairy cow diets has been increasing since the early 1990s (Lubulwa and Shafron 2007). Grain does not just replace pastures but may also be provided as a complement to increase total energy intake and increase milk production. The role of grain and concentrates in boosting milk production is not considered in this paper: we are targeting a given production level of milk, and any grain provided would replace one of the other feed types.

Ho *et al.* (2007) assume that bought-in feed is a mix of grain and conserved fodder, rather than adjusting this based on what is happening with on-farm fodder production. This is a good question: how much is the amount of bought-in feed just a fixed ratio?

The farmer's problem is to minimise variable costs of feeding a single cow. Ho *et al.* (2005) notes that economies of scale are often not significant for dairy, implying that results gleaned for a single cow might also have regional relevance.

Variable costs are defined as the sum of the following components:

- irrigation water costs (opportunity cost plus delivery cost times irrigation water used);
- the cost of converting areas from annual pasture to perennial pasture or from perennial pasture to annual pasture (we allow irrigators to choose optimal areas of annual and perennial pastures);
- the cost of cutting and conserving any annual pastures as hay;
- the cost of oversowing perennial pastures not irrigated through summer;
- feed grain costs;
- bought-in hay costs.

More formally, the choice variables are areas of annual pastures to irrigate in spring (including any area converted from perennial pasture) and autumn; areas of annual pastures to cut in spring; amounts of home-grown hay to feed out in summer, autumn and winter; areas of perennial pastures to irrigate in spring (including any area converted from annual pasture), summer and autumn; and amounts of feed grain and hay to buy-in each season.

The quantity of dry matter produced from pastures each season depends not only on current season rainfall and irrigation but also on rainfall and irrigation water applied in previous seasons. Information provided by Victorian DPI has been simplified to the current year impacts for the purposes of this modelling, so some of the disadvantages of not irrigating in autumn have not been captured. For the purposes of this modelling, it is assumed to be a dry year. See Appendix 1 for a schematic of pasture accumulation given different choices in the present and past season. It is assumed that all pastures have been well irrigated in the past.

Total energy required is based mostly on milk production in that season, with pregnancy also increasing energy requirements. Milk production characteristics differ quite dramatically between spring and autumn calvers. Cows which calve in spring tend to have a large early lactation peak, and a relatively rapid decline later through autumn. Cows which calve in autumn on the other hand, do not seem to experience the same early peak but tend to have more persistent yields later in the lactation. These characteristics are built into cow energy requirements in this modelling (Walker *et al.* 2007).

The model has been modified to allow results to be derived for three patterns of calving. In the first case, the 'cow' to be fed has taken on the average pregnancy and milk production profile for the region. The second and third cases look at minimal cost feeding for spring and autumn calvers respectively.

The cost minimisation problem is subject to a number of constraints:

- land constraints: farmers cannot irrigate more land than is available, and land which has been previously irrigated has a different productivity to that which was not irrigated in previous seasons.
- A hay constraint: Farmers cannot feed out more home-grown hay than has been cut. We assume that 15 per cent of annual pasture dry matter is lost in the cutting,

and storing. An additional 15 per cent is wasted in the feeding out process, for both home-grown and bought-in hay.

- An energy constraint: total energy provided must be greater than a minimum requirement each season.
- A protein constraint: average protein as a percentage of dry matter must exceed minimum requirements each season.
- A fibre constraint: average fibre as a percentage of dry matter must exceed minimum requirements each season.
- A density constraint: average density must exceed the minimum requirement.
- A positivity constraint: all variables must be greater than or equal to zero.

Please see Appendix 1 for a full description of the linear programming model.

3. Calibration of results: three recent years

Scenario 1: A typical pre-2000 year

This scenario represents a typical pre-2000 year, where both the price of water on the water market and hay and feed grain were relatively cheap. In addition, reflecting the trend to bigger herds on less land, we assume a lower stocking rate for this scenario relative to the next two scenarios. We set prices on the temporary water market at $50/ML, the price of hay at $120/tonne and the price of feed grain at $180/tonne.

Spring calver

At these prices, feed for cattle is exclusively home-grown. Because pastures makes up so much of the diet, the fibre, protein and density constraints are easily met, and the problem is basically one of providing sufficient energy.

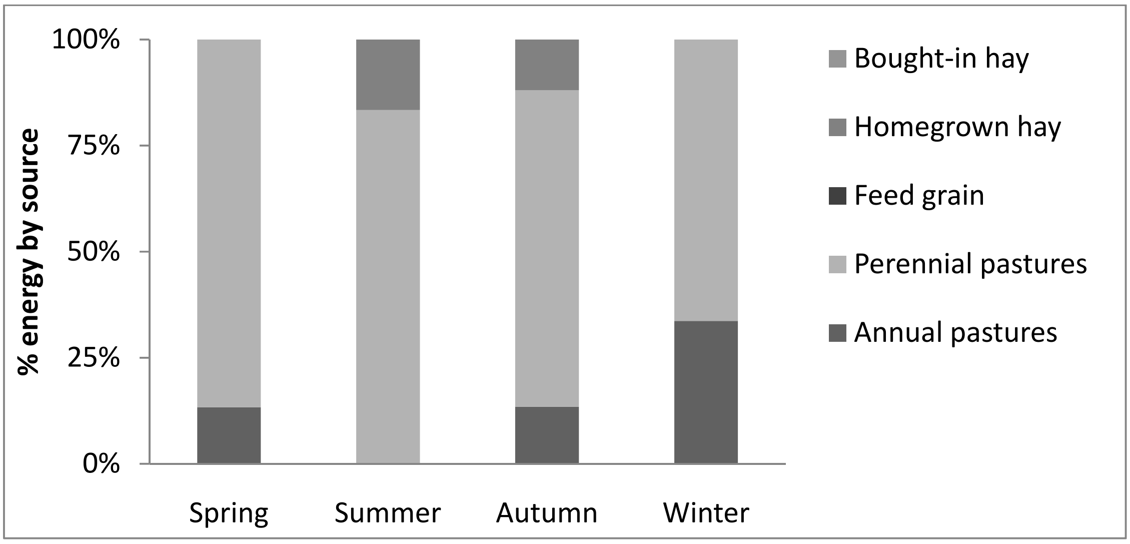

Figure 1: Sources of energy (%) by season for a spring-calving cow, scenario 1

All existing areas of annual pasture are irrigated in spring, but about three-quarters of the dry matter produced from annual pastures is conserved to feed out later in the year. The remaining area is grazed, to make up just under 20 per cent of the energy requirements for spring, with the other 80 per cent coming from perennial pastures, both irrigated and dry land.

In summer, perennial pastures are again the primary source of energy (just over 80 per cent of total energy requirements), with hay cut in spring fed out to make up the remaining 20 per cent.

In autumn, annual and perennial pastures are supplemented with the remaining conserved fodder. These autumn-irrigated pastures are sufficient to provide feed through winter: though pasture accumulation is lower through winter, so is demand for energy as spring-calving cows are dried off.

Autumn calver

Although dairy farmers face the same set of prices as for the spring calving cows above, the least-cost feed solution for an autumn calving cow is somewhat different, driven by the different seasonal energy requirements of the autumn-calving cow. Energy requirements for the autumn-calving cow are high in winter and spring but lower through summer and autumn. Because of this different pattern of energy demands, some perennial pasture is converted to annual pasture, which has higher rates of pasture accumulation through these seasons.

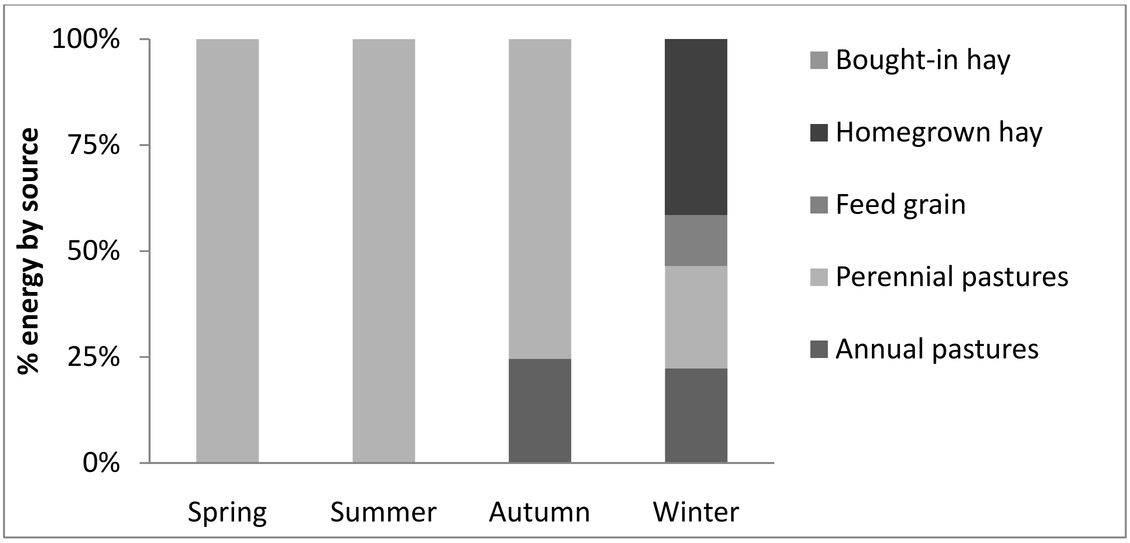

Figure 2: Sources of energy (%) by season for a autumn-calving cow, scenario 1

In spring and summer, perennial pastures provide 100 per cent of the energy requirements for the cow. The farmer has converted some area of perennial pasture to annual pasture, but this is locked out for conservation in spring. As summer is a relatively low milk production time for the cow, energy requirements are lower and smaller area of perennial pasture is irrigated than for the spring-calver.

Pastures are sufficient to cover autumn energy demands, but since winter energy requirements are high, and this is a time of relatively low pasture growth, pastures are supplemented with the hay cut in spring and also bought-in feed grain.

Regional feed costs for Scenario 1

In this section, we model the least-cost feeding of an ‘average’ dairy cow, with energy requirements based on the weighted-average of pregnancy status across the region. In the northern Victorian region, about 30 per cent of the herd is spring calving, around 60 per cent are split or batch calving, and the remaining 10 per cent calve for year-round milk production (Dairy Australia 2009). Considering the least-cost feeding of a cow with an ‘average’ pregnancy profile allows us to consider average feed composition for the region, for use in regional modelling.

Not surprisingly, the optimal feed mix for the average cow lies somewhere between the solutions for spring and autumn calvers. Energy requirements are made up from a mix of annual and perennial pastures, with a significant portion of annual pastures locked out for conservation in spring, fed out in summer and winter, and a little bit of feed grain also used in winter. Irrigation water is applied at a rate of 2.66 ML/cow per year.

We have broadly captured the typical feeding system of the region in this period, with perhaps the biggest difference being to underestimate provision of feed grains. Through the 1990s, use of feed grain increased through the region, with the percentage of farms using supplementary feeds in manufacturing milk states increasing from 72 per cent in 1991-92 to 85 per cent in 1997-98 (Martin *et al.* 2000). In 1997-98, farmers in Victoria provided total supplementary feed of about 0.75 tonnes per cow, of which feed grains comprised about two-thirds. This was low relative to other states.

This may be partly due to the fact that we do not consider the role of grain and concentrates in boosting milk production. Also, in our modelling of pre-2000 conditions, the land constraint is not binding, that is, farmers do not have to fully irrigate all areas to provide sufficient energy. Perhaps our assumptions regarding stocking rates were too low: modelled grain usage might have been higher if irrigable area per cow were lower.

Scenario 2: 2004-05, scarcer water

From 2002-03, water has been much scarcer in northern Victoria, and the price on the temporary water market much higher. In 2004-05, allocations were reasonably high, but not as high as in the past, and feed grain and hay were back at long-term averages after the spikes of 2002-03. For this scenario, we assume prices for temporary water market price of $150/ML, hay of $120/tonne and feed grain of $180/tonne.

Recall as well that we assume a higher stocking rate than previously: a total of 0.32 irrigable hectares per milking cow, split initially 0.24 hectares to perennial pastures and 0.08 to annual pastures.

Spring calver

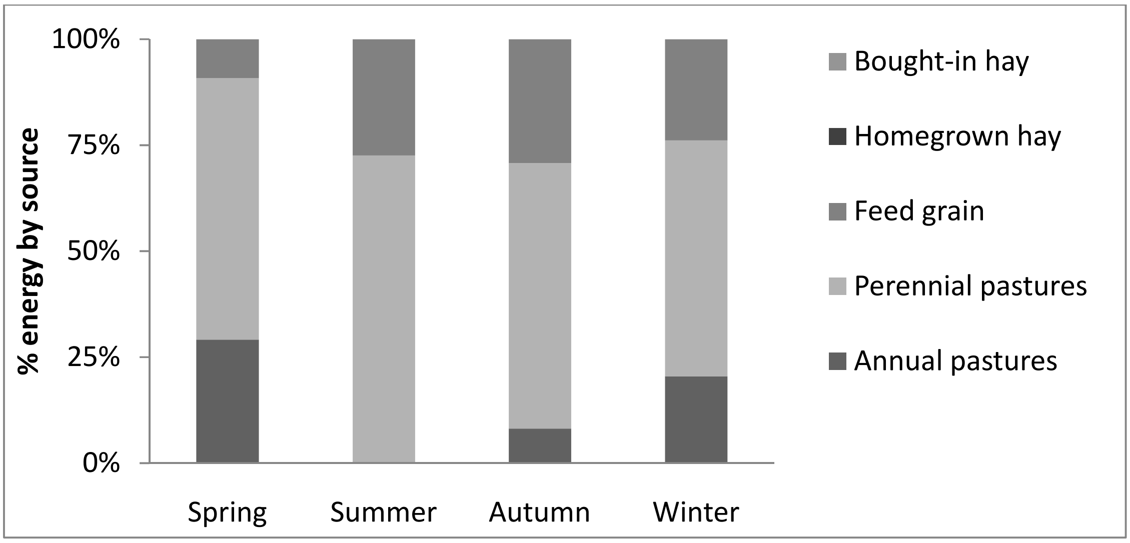

Figure 3: Sources of energy (%) by season for a spring-calving cow, scenario 2

The feeding regime is again based on the irrigation of pastures. The main differences between this scenario and the one above are that all pastures are grazed, whereas above significant portions of annual pastures were cut and conserved, and feed grain takes a more prominent role in the diet. In this case, given the higher stocking rate and costs associated with conserving and feeding out fodder, it is more cost-effective to graze annual pastures in spring.

Autumn calver

In keeping with the higher energy requirements in winter for an autumn-calving cow, a small area of perennial pasture is converted to annual pasture, which produces more dry matter in winter. As energy requirements are relatively low in summer, this lesser area of perennial pasture provides sufficient feed in this season.

Feed grain plays a major role in the diet in winter, with some hay also bought-in to provide sufficient fibre.

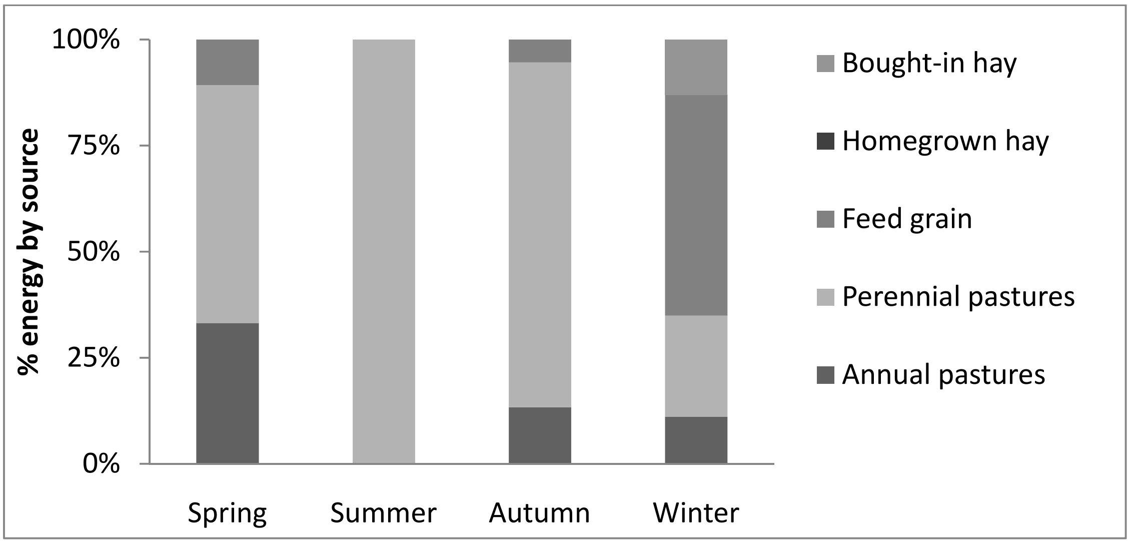

Figure 4: Sources of energy (%) by season for an autumn-calving cow, scenario 2

Regional feed costs for Scenario 2

At a regional level, this modelling predicts that for a year similar to 2004-05, the majority of feed requirements come from irrigated pastures, ranging from 87 per cent of the total seasonal requirement in spring to 48 per cent in winter. This seems broadly in accordance with Ho *et al.* (2005), who report that within the region, the amount of energy bought-in to farms varies between 0 per cent and 75 per cent, with an average of 60 per cent of energy provided through home pastures. This involves an irrigation water application of 2.13 ML/cow over the year, just over three-quarters that used in Scenario 1.

We model feed grain use of just over 1 tonne/cow, consistent with the average of 1.2 tonnes per cow reported by Dairy Australia (2005). In our modelling, no hay is produced on-farm and very little is bought-in. We were unable to find data on production or feeding of hay/silage for this time period, but it seems likely that the modelling has underestimated this, perhaps overestimating irrigation of pastures somewhat.

Scenario 3: 2006-07, extreme drought

In 2006-07, allocations of water for irrigation in the Goulburn system were at the lowest ever, at only 29 per cent. Prices on the water market skyrocketed, but so did prices for bought-in substitutes. Prices for this scenario are assumed to be $750/ML for temporary water, and $350/tonne each for hay and feed grain.

Spring calver

In this scenario, there is a pronounced switch away from perennial pastures and towards annual pastures, which provide greater dry matter per ML, driven by the high opportunity cost of water use. Only a small amount of perennial pastures remain, required to maintain a balanced diet in summer. A small portion of the annual pastures are locked out for conservation in spring.

Bought-in hay and feed grain play a much bigger role in the feed budget. Hay, the bulk of which is bought-in, provides close to 60 per cent of energy requirements in summer. Feed grain provides almost 60 per cent of energy requirements in autumn, and just over 40 per cent in winter. As the requirement for protein has dropped off in autumn relative to summer for a spring calving cow, feed grain, which is relatively low in protein, can increase to provide a greater proportion of the energy balance.

Irrigation of annual pastures drops away in autumn (by about one-third). As the focus of this modelling is on the feeding of a cow over a single year, it underestimates the role that irrigating pastures in autumn has on pasture accumulation in the following irrigation season: an autumn irrigation not only provides feed in that season but also maintains pastures in good condition through to next spring.

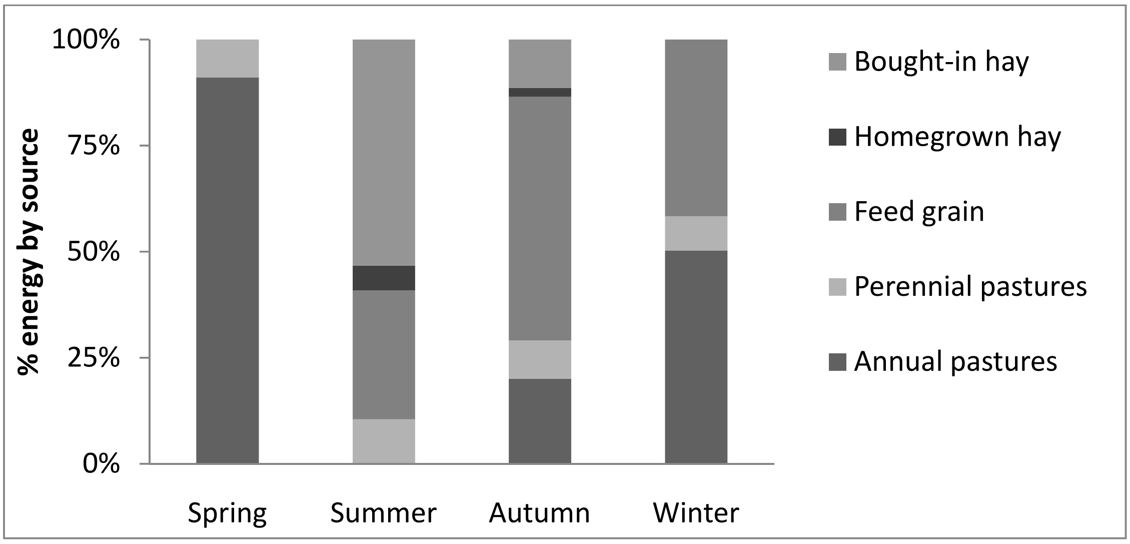

Figure 5: Sources of energy (%) by season for a spring-calving cow, scenario 3

Autumn calver

As is the case for the spring calver above, the 2006-07 conditions see a large conversion from perennial pastures to annual pastures: as energy requirements for autumn calvers are high in winter, all annual pastures are irrigated in autumn to support winter feeding. Relative to the spring calver, the autumn calver is fed more grain and less hay.

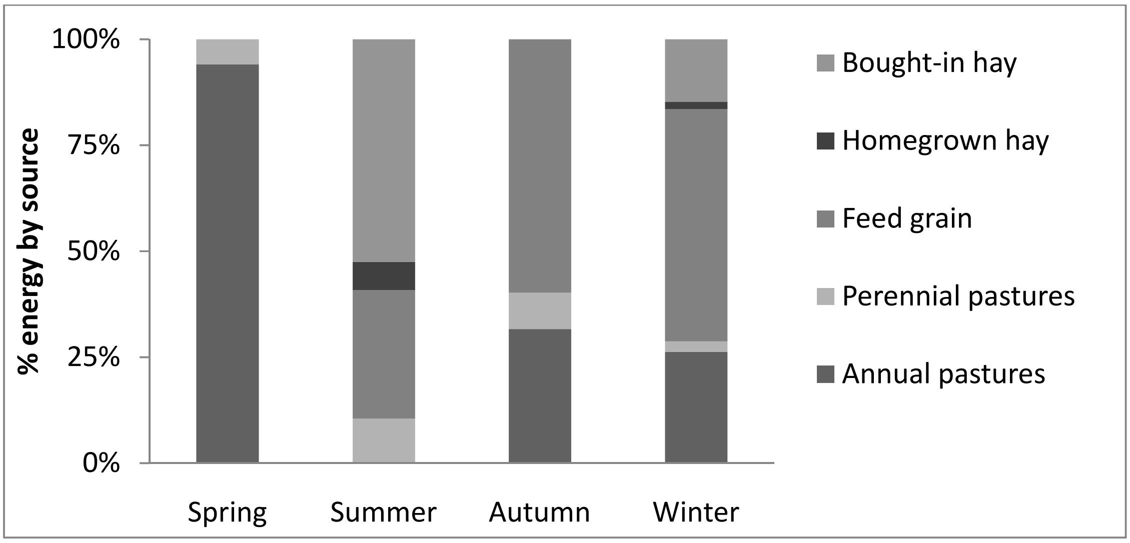

Figure 6: Sources of energy (%) by season for a spring-calving cow, scenario 3

Regional feed perspective for Scenario 3

Actual annual grain usage in 2006-07 was 1.4 tonnes/cow (Dairy Australia 2007), close to our modelled results of 1.7 tonnes/cow. The modelling also predicted 1.4 tonnes/cow of hay were bought. At $350/tonne, this equates to modelled spending of about $1000/cow on bought-in fodder. This is perhaps a little higher than actual average fodder costs for 2006-07, though these were very high historically, at close to 50 per cent of total cash costs.

On average, Dairy Australia (2009) reports irrigation water use of around 1.2 ML/cow for the northern Victoria/Riverina area. For 2006-07 conditions, we model water use of around 0.8 ML/cow. Energy derived from pastures varies between 100 per cent in spring

Summary of the results and general observations

Based on available data, it appears the linear programming model has done an acceptable job of predicting how dairy farmers might feed their cows under changing prices for inputs.

The modelling predicts that at these prices, there is a marked conversion of land from perennial pastures to annual pastures. While this may have occurred to some extent (Ho *et al.* 2007), whether it has to the extent indicated in Scenario 3 (where annual pastures increase from 25 per cent to 90 per cent of irrigable area) is doubtful.

In scenarios 1 and 2, the spring-calving cow was cheaper to feed than the autumn-calving cow; by scenario 3, while feed costs had increased for all types of cows, the spring-calving cow was the more expensive to feed. This matches actual calving patterns in the region, which have seen a shift away from spring calving. (There are also premiums associated with producing milk in different seasons.)

On our measure of costs (which values all water at its opportunity cost and excludes other costs such as fertilizer, labour and fuel), costs associated with feeding a dairy cow more than doubled from Scenario 1 to Scenario 2, and then more than doubled again from Scenario 2 to Scenario 3. Although this measure does not entirely capture farmer variable costs, it is an indication of the pressure arising from feed costs that dairy farmers have faced over the past decade.

Balancing the diet has also become more difficult as the role of pastures has diminished. This is reflected in the modelling by the number of binding nutritional constraints. In Scenario 1, when pastures were the primary source of feed, fibre, protein and density constraints were met easily and automatically. In Scenario 3, providing sufficient protein became an issue in summer and autumn, and providing sufficient fibre became an issue in winter. In addition, the use of hay in summer had to be balanced against the need to maintain energy density above 10,000 MJ/tonne of dry matter. In real life, further complicating matters, there is also significant variability within feed types as well as between feed types.

4. Substitutability between inputs: estimating a CES substitution parameter

The CGE models developed at Centre of Policy Studies mostly use constant elasticity of substitution (CES) functions to model choice between inputs for both production and consumption choices.

The linear programming and CES approaches to modelling choices are substantially different. In linear programming, inputs are perfectly substitutable up to a certain limit, after which they are not substitutable at all. In CES functions on the other hand, there is always some degree of substitution possible between inputs, with the degree of change in response to relative price movements captured in a substitution parameter.

We established in the previous section that the linear programming model does an adequate job of mimicking real-world responses to changing water, feed grain and hay prices. Thus, output from the linear program might be used to inform estimates of the CES substitution parameter for inputs to milk production.

In the CGE model used to analyse regional water issues in Australia, TERM-H20, these inputs are divided into two separate nests. Effective land is a CES nest of irrigable and dry land (this is where irrigation water enters the farmer's decision making problem). In another CES nest, feed grains from different regions are combined to form a total feed grain input. Bought-in hay is also represented at this level.

We will abstract from this two-nest distinction for the moment by simply having water, feed grain and hay all substituting in a single CES function to provide sufficient feed.

The CES production function takes the form:

$$Z = \left(\sum_i \delta_i X_i^{-\rho} \right)^{-\frac{1}{\rho}}$$

Where the Z is output, X are the inputs, δ are weights often derived from cost shares, and ρ is the substitution parameter, which represents how substitutable one input is for another.

The demand curve for one input derived from the related cost minimisation problem is:

$$X_k = Z \delta_k^{\frac{1}{\rho+1}} \left[\frac{P_k}{P_{ave}} \right]^{-\frac{1}{\rho+1}}$$

Where

$$P_{ave} = \left(\sum_i \delta_i^{1/(\rho+1)} P_i^{\rho/(\rho+1)} \right)^{(\rho+1)/\rho}$$

We will use the linear programming model to estimate the substitution parameter ρ**.**

The blue line in the graph below is derived from the linear programming model. It shows how the annual demand for irrigation water varies as the price of temporary water varies, with the price of other inputs held constant at \$120/tonne for hay and \$180/tonne for feed grain. The green line represents the estimated CES demand curve. We used the MATLAB function nlinfit (non-linear regression fitting) to estimate parameters for the CES relationship which best fits the linear programming demand curve. The substitution parameter is estimated at 0.7, as opposed to the 0.2 currently in TERM-H20.

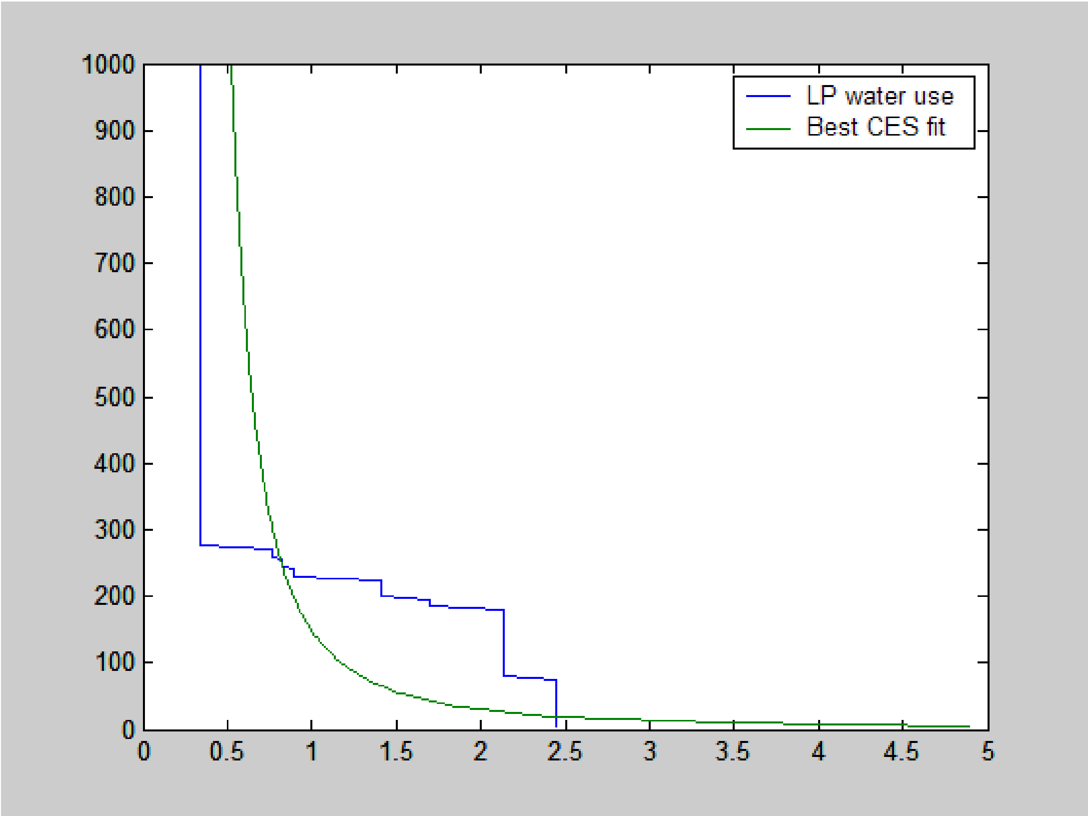

Figure 7: Demand for irrigation water, linear programming versus CES

A CES demand curve is not able to capture how quickly irrigators might switch back into water as the opportunity cost of water use falls. It also fails to pick up the natural limits to water use: in the short run, there is no point applying water once land limits are met or sufficient feed has been provided.

5. Conclusions

This paper has developed a linear programming model of least-cost feeding of a dairy cow in northern Victoria. This was conducted separately for a spring-calving cow, an autumn-calving cow and a 'cow' representing a profile of energy demands typical of the region as a whole.

Composition of feed changed radically as relative prices changed, from systems based almost entirely on the irrigation of perennial pastures to a system involving a large-scale conversion of perennial pastures to annual pastures and a heavy reliance on bought-in feeds. The linear programming model seemed to adequately capture actual patterns in the provision of feed under different conditions.

Output from the linear programming model was used to calibrate a CES function, as used in the CGE models developed at Centre of Policy Studies. The substitution parameter was estimated at 0.7, rather than the 0.2 originally used, indicating a greater degree of substitution between water and other inputs than first assumed. It might be noted that, even at best fit, a CES function is not able to capture the shape of the demand curve derived from the linear programming model, in particular, just how elastic demand might be over certain ranges.

Feeding of dairy cows has become vastly more expensive over the past decade. This has largely been due to lower availability and hence increases in the price of irrigation water, though prices of other feed inputs such as hay and feed grain have also shown significant volatility and periods of extremely high prices. The modelling in this paper has assumed that the cow will continue to be fed to produce a given amount of milk, regardless of the cost. At some stage, costs, especially relative to revenues, will be sufficiently high that farmers will question whether, or to what degree (for example, drying off early to reduce feed bills), to feed cattle through this.

In some years, for example, early 2008, farmgate milk prices in the region (largely based on the world price) have been strong, cushioning farmers from the impact of high input prices. Prices collapsed in late 2008, leaving many dairy farmers in the region unable to cover costs. Dairy Australia (2009) reports that 41 per cent of dairy farmers in the region are considering reducing milking numbers and 17 per cent are considering exiting the industry in the next 12 months. At the time of printing, 2009-10 milk production was expected to decline by 9 per cent on the previous year, and confidence in the future was at all-time lows.

This modelling abstracts from those major sorts of shifts, merely asking the least-cost way of producing a given level of milk from a single cow as relative prices shift.

A future working paper develops an optimal replacement model for dairy cows in northern Victoria, considering optimal replacement in ‘normal’ conditions, and culling as a response to drought.

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Appendix 1: The linear programming model

This section develops a linear programming model of the minimum cost feed problem for dairy cows. Please refer to notation list later in this Appendix.

The farmer's problem is to minimise costs associated with feeding dairy cows. These are captured in Equation 1 below, which includes terms for the cost of irrigation water use (the opportunity cost of water (the market price) plus delivery cost)[2]; feed grain costs; bought-in hay costs; the cost of cutting and conserving home-grown hay; the cost of oversowing perennial pastures not irrigated through summer; and the cost of converting land from annual pastures to perennial pasture or vice versa.

$$\begin{aligned}\text{Min}\left\{\text{costs}\right\} &= (twp + p_w)(a_1^1 w_a^1 + a_{21}^1 w_a^1 + (a_{11}^3 + a_{01}^3) w_a^3 + p_1^1 w_p^1 + p_2^1 w_p^1 + p_{11}^2 w_p^2 + p_{11}^2 w_p^3 \\ &+ p_{01}^3 (1.5 + w_p^3)) + p_f^t f^t + p_h^t h^t + p_c a_c^1 + Op_{01}^3 + O_a a_2^1 + O_p p_2^1\end{aligned} \tag{1}$$

This cost minimisation takes place subject to a number of constraints.

<u>Land constraints</u>

Farmers cannot irrigate more land than is available. Areas previously devoted to annual pastures may be converted to perennial pastures; if this occurs, these new perennial pasture areas must be irrigated in spring. Areas previously devoted to perennial pastures may be converted to annual pastures; from there they may be irrigated or left to grow dryland. It is assumed that this decision is made once (before the start of the irrigation season) and then areas are held fixed for the remainder of the modelling.

$$a_1^1 \le AP \tag{2}$$

$$a_c^1 \le a_1^1 + a_{21}^1 \tag{3}$$

$$a_{21}^1 \le a_2^1 \tag{4}$$

[2] Note that to irrigate perennial pastures in autumn that were not irrigated through summer requires an additional 1.5 ML/hectare.

$$a_2^1 \le PP \tag{5}$$

$$a_{11}^3 \le a_1^1 + a_{21}^1 \tag{6}$$

$$a_{01}^3 \le AP + a_2^1 - p_2^1 - a_1^1 - a_{21}^1 \tag{7}$$

$$p_1^1 \le PP \tag{8}$$

$$p_2^1 \le AP \tag{9}$$

$$p_{11}^2 \le p_1^1 + p_{21}^1 \tag{10}$$

$$p_{01}^3 \le PP + p_2^1 - a_2^1 - p_{11}^2 \tag{11}$$

$$a_1^1 + a_2^1 + p_1^1 + p_2^1 \le AP + PP \tag{12}$$

<u>Hay constraint</u>

Farmers cannot feed out more home-grown hay than has been cut. We assume that 15 per cent of annual pasture dry matter is lost in the cutting and storing process.

$$h_c^2 + h_c^3 \le 0.85 \times \frac{DM_a^1}{ha} \times a_c^1 \tag{13}$$

<u>Nutrition constraints</u>

<u>Energy</u>

Total energy (MJ) provided must be greater than requirements each season. Equation (14) refers to the energy constraint for spring, equation (15) to the energy constraint for summer, and so on. The other nutritional constraints below are also set out as one constraint per season.

Energy provided by pastures is calculated as hectares (for pastures), multiplied by dry matter (tonnes) per hectare, multiplied by megajoules (MJ) per tonne of dry matter. Note that choosing not to irrigate pastures in the current or previous season attracts a dry matter production penalty. For example, dry matter production from dryland pastures is only 30 per cent of irrigated levels in the equation (14) below. These relationships are shown diagrammatically in Appendix 3 below.

For grains and hay, energy is calculated as dry matter per tonne multiplied by MJ per tonne of dry matter.

Energy requirements depend on milk production, pregnancy and maintenance. Milk production and pregnancy status differ between seasons depending on whether the cow is a spring or an autumn calver. In the past, spring (seasonal) calving was dominant in northern Victoria, but other patterns of production have become more common in recent years.

$$\begin{aligned}&(a_1^1 + a_{21}^1 - a_c^1 + (AP + a_2^1 - p_2^1 - a_1^1 - a_{21}^1) \times 0.3) \times \frac{DM_a^1}{ha} \times \frac{MJ_a}{DM} \\ &+ (p_1^1 + p_2^1 + (PP - a_2^1 - p_1^1) \times 0.3) \times \frac{DM_p^1}{ha} \times \frac{MJ_p}{DM} \\ &+ f^1 \times \frac{DM_f}{t} \times \frac{MJ_f}{DM} + 0.85 \times h^1 \times \frac{DM_h}{t} \times \frac{MJ_h}{DM} \geq MJ^1\end{aligned} \tag{14}$$

$$\begin{aligned}&(p_{11}^2 + (p_1^1 + p_2^1 - p_{11}^2) \times 0.05) \times \frac{DM_p^2}{ha} \times \frac{MJ_p}{DM} \\ &+ f^2 \times \frac{DM_f}{t} \times \frac{MJ_f}{DM} + 0.85 \times (h^2 \times \frac{DM_h}{t} + h_c^2) \times \frac{MJ_h}{DM} \geq MJ^2\end{aligned} \tag{15}$$

$$\begin{aligned}&(a_{11}^3 + (a_1^1 + a_{21}^1 - a_{11}^3) \times 0.1 + a_{01}^3 \times 0.9 + (AP + a_2^1 - p_2^1 - a_1^1 - a_{21}^1 - a_{01}^3) \times 0.05) \times \frac{DM_a^3}{ha} \times \frac{MJ_a}{DM} \\ &+ (p_{11}^2 + p_{01}^3 \times 0.2 + (PP + p_2^1 - a_2^1 - p_{11}^2 - p_{01}^3) \times 0.05) \times \frac{DM_p^3}{ha} \times \frac{MJ_p}{DM} \\ &+ f^3 \times \frac{DM_f}{t} \times \frac{MJ_f}{DM} + 0.85 \times (h^3 \times \frac{DM_h}{t} + h_c^3) \times \frac{MJ_h}{DM} \geq MJ^3\end{aligned} \tag{16}$$

$$\begin{aligned}&(a_{11}^3 + (a_1^1 + a_{21}^1 - a_{11}^3) \times 0.1 + a_{01}^3 \times 0.9 + (AP + a_2^1 - p_2^1 - a_1^1 - a_{21}^1 - a_{01}^3) \times 0.05) \times \frac{DM_a^4}{ha} \times \frac{MJ_a}{DM} \\ &+ (p_{11}^2 + p_{01}^3 \times 0.2 + (PP + p_2^1 - a_2^1 - p_{11}^2 - p_{01}^3) \times 0.05) \times \frac{DM_p^4}{ha} \times \frac{MJ_p}{DM} \\ &+ f^4 \times \frac{DM_f}{t} \times \frac{MJ_f}{DM} + 0.85 \times (h^4 \times \frac{DM_h}{t} + 0.85 \times a_c^1 \times \frac{DM_a^1}{ha} - h_c^2 - h_c^3) \times \frac{MJ_h}{DM} \geq MJ^4\end{aligned} \tag{17}$$

Protein

Average protein as a percentage of dry matter must exceed minimum requirements.

$$(a_1^1 + a_{21}^1 - a_c^1 + (AP + a_2^1 - p_2^1 - a_1^1 - a_{21}^1) \times 0.3) \times \frac{DM_a^1}{ha} \times (P_p^1 - P^1)$$
$$+ (p_1^1 + p_2^1 + (PP - a_2^1 - p_1^1) \times 0.3) \times \frac{DM_p^1}{ha} \times (P_p^1 - P^1)$$
$$+ f^1 \times \frac{DM_f}{t} \times (0.108 - P^1) + 0.85 \times h^1 \times \frac{DM_h}{t} \times (0.189 - P^1) \geq 0 \tag{18}$$

$$(p_{11}^2 + (p_1^1 + p_2^1 - p_{11}^2) \times 0.05) \times \frac{DM_p^2}{ha} \times (P_p^2 - P^2)$$
$$+ f^2 \times \frac{DM_f}{t} \times (0.108 - P^2) + 0.85 \times (h^2 \times \frac{DM_h}{t} + h_c^2) \times (0.189 - P^2) \geq 0 \tag{19}$$

$$(a_{11}^3 + (a_1^1 + a_{21}^1 - a_{11}^3) \times 0.1 + a_{01}^3 \times 0.9 + (AP + a_2^1 - p_2^1 - a_1^1 - a_{21}^1 - a_{01}^3) \times 0.05) \times \frac{DM_a^3}{ha} \times (P_p^3 - P^3)$$
$$+ (p_{11}^2 + p_{01}^3 \times 0.2 + (PP + p_2^1 - a_2^1 - p_{11}^2 - p_{01}^3) \times 0.05) \times \frac{DM_p^3}{ha} \times (P_p^3 - P^3)$$
$$+ f^3 \times \frac{DM_f}{t} \times (0.108 - P^3) + 0.85 \times (h^3 \times \frac{DM_h}{t} + h_c^3) \times (0.189 - P^3) \geq 0 \tag{20}$$

$$(a_{11}^3 + (a_1^1 + a_{21}^1 - a_{11}^3) \times 0.1 + a_{01}^3 \times 0.9 + (AP + a_2^1 - p_2^1 - a_1^1 - a_{21}^1 - a_{01}^3) \times 0.05) \times \frac{DM_a^4}{ha} \times (P_p^4 - P^4)$$
$$+ (p_{11}^2 + p_{01}^3 \times 0.2 + (PP + p_2^1 - a_2^1 - p_{11}^2 - p_{01}^3) \times 0.05) \times \frac{DM_p^4}{ha} \times (P_p^4 - P^4)$$
$$+ f^4 \times \frac{DM_f}{t} \times (0.108 - P^4)$$
$$+ 0.85 \times (h^4 \times \frac{DM_h}{t} + 0.85 \times a_c^1 \times \frac{DM_a^1}{ha} - h_c^2 - h_c^3) \times (0.189 - P^4) \geq 0 \tag{21}$$

Fibre

Average fibre as a percentage of dry matter must exceed minimum requirements.

$$
\begin{aligned}
&(a_1^1 + a_{21}^1 - a_c^1 + (AP + a_2^1 - p_2^1 - a_1^1 - a_{21}^1) \times 0.3) \times \frac{DM_a^1}{ha} \times (0.45 - F^1) \\
&+(p_1^1 + p_2^1 + (PP - a_2^1 - p_1^1) \times 0.3) \times \frac{DM_p^1}{ha} \times (0.45 - F^1) \\
&+ f^1 \times \frac{DM_f}{t} \times (0.2 - F^1) + 0.85 \times h^1 \times \frac{DM_h}{t} \times (0.447 - F^1) \geq 0
\end{aligned} \tag{22}
$$

$$
\begin{aligned}
&(p_{11}^2 + (p_1^1 + p_2^1 - p_{11}^2) \times 0.05) \times \frac{DM_a^2}{ha} \times (0.45 - F^2) \\
&+ f^2 \times \frac{DM_f}{t} \times (0.2 - F^2) + 0.85 \times (h^2 \times \frac{DM_h}{t} + h_c^2) \times (0.447 - F^2) \geq 0
\end{aligned} \tag{23}
$$

$$
\begin{aligned}
&(a_{11}^3 + (a_1^1 + a_{21}^1 - a_{11}^3) \times 0.1 + a_{01}^3 \times 0.9 + (AP + a_2^1 - p_2^1 - a_1^1 - a_{21}^1 - a_{01}^3) \times 0.05) \times \frac{DM_a^3}{ha} \times (0.45 - F^3) \\
&+(p_{11}^2 + p_{01}^3 \times 0.2 + (PP + p_2^1 - a_2^1 - p_{11}^2 - p_{01}^3) \times 0.05) \times \frac{DM_p^3}{ha} \times (0.45 - F^3) \\
&+ f^3 \times \frac{DM_f}{t} \times (0.2 - F^3) + 0.85 \times (h^3 \times \frac{DM_h}{t} + h_c^3) \times (0.447 - F^3) \geq 0
\end{aligned} \tag{24}
$$

$$
\begin{aligned}
&(a_{11}^3 + (a_1^1 + a_{21}^1 - a_{11}^3) \times 0.1 + a_{01}^3 \times 0.9 + (AP + a_2^1 - p_2^1 - a_1^1 - a_{21}^1 - a_{01}^3) \times 0.05) \times \frac{DM_a^4}{ha} \times (0.45 - F^4) \\
&+(p_{11}^2 + p_{01}^3 \times 0.2 + (PP + p_2^1 - a_2^1 - p_{11}^2 - p_{01}^3) \times 0.05) \times \frac{DM_p^4}{ha} \times (0.45 - F^4) \\
&+ f^4 \times \frac{DM_f}{t} \times (0.2 - F^4) + 0.85 \times (h^4 \times \frac{DM_h}{t} + 0.85 \times a_c^1 \times \frac{DM_a^1}{ha} - h_c^2 - h_c^3) \times (0.447 - F^4) \geq 0
\end{aligned} \tag{25}
$$

Density

Average density must exceed the minimum requirement.

$$
\begin{aligned}
&(a_1^1 + a_{21}^1 - a_c^1 + (AP + a_2^1 - p_2^1 - a_1^1 - a_{21}^1) \times 0.3) \times \frac{DM_a^1}{ha} \times (MJ_a - D) \\
&+(p_1^1 + p_2^1 + (PP - a_2^1 - p_1^1) \times 0.3) \times \frac{DM_p^1}{ha} \times (MJ_p - D) \\
&+ f^1 \times \frac{DM_f}{t} \times (MJ_f - D) + 0.85 \times h^1 \times \frac{DM_h}{t} \times (MJ_h - D) \geq 0
\end{aligned} \tag{26}
$$

$$(p_{11}^2 + (p_1^1 + p_2^1 - p_{11}^2) \times 0.05) \times \frac{DM_p^2}{ha} \times (MJ_p - D)$$
$$+ f^2 \times \frac{DM_f}{t} \times (MJ_f - D) + 0.85 \times (h^2 \times \frac{DM_h}{t} + h_c^2) \times (MJ_h - D) \geq 0 \qquad (27)$$

$$(a_{11}^3 + (a_1^1 + a_{21}^1 - a_{11}^3) \times 0.1 + a_{01}^3 \times 0.9 + (AP + a_2^1 - p_2^1 - a_1^1 - a_{21}^1 - a_{01}^3) \times 0.05) \times \frac{DM_a^3}{ha} \times (MJ_a - D)$$
$$+(p_{11}^2 + p_{01}^3 \times 0.2 + (PP + p_2^1 - a_2^1 - p_{11}^2 - p_{01}^3) \times 0.05) \times \frac{DM_p^3}{ha} \times (MJ_p - D)$$
$$+ f^3 \times \frac{DM_f}{t} \times (MJ_f - D) + 0.85 \times (h^3 \times \frac{DM_h}{t} + h_c^3) \times (MJ_h - D) \geq 0 \qquad (28)$$

$$(a_{11}^3 + (a_1^1 + a_{21}^1 - a_{11}^3) \times 0.1 + a_{01}^3 \times 0.9 + (AP + a_2^1 - p_2^1 - a_1^1 - a_{21}^1 - a_{01}^3) \times 0.05) \times \frac{DM_a^4}{ha} \times (MJ_a - D)$$
$$+(p_{11}^2 + p_{01}^3 \times 0.2 + (PP + p_2^1 - a_2^1 - p_{11}^2 - p_{01}^3) \times 0.05) \times \frac{DM_p^4}{ha} \times (MJ_p - D)$$
$$+ f^4 \times \frac{DM_f}{t} \times (MJ_f - D) + 0.85 \times (h^4 \times \frac{DM_h}{t} + 0.85 \times a_c^1 \times \frac{DM_a^1}{ha} - h_c^2 - h_c^3) \times (MJ_h - D) \geq 0 \qquad (29)$$

Plus a positivity constraint: all variables must be greater than or equal to zero.

Notation

Superscript ^{t} used for time, with 1 = spring through to 4 = winter.

<u>Variables</u>

a_1^1 area of annual pasture irrigated in spring (ha)

a_c^1 area of annual pasture cut in spring (ha)

a_{11}^3 area of annual pasture irrigated in autumn, following an irrigated spring (ha)

a_{01}^3 area of annual pasture irrigated in autumn, following a non-irrigated spring (ha)

p_1^1 area of perennial pasture irrigated in spring (ha)

p_{11}^2 area of perennial pasture irrigated in summer, following a spring irrigation (ha)

p_{01}^{3} area of perennial pasture irrigated in autumn, after a non-irrigated summer (ha)

f^{t} feed grain bought in season t (tonnes)

h^{t} hay bought onto the property in season t (tonnes)

h_{c}^{t} home-grown hay fed out in season t (t = 2, 3, 4) (tonnes)

<u>Parameters that vary with hydroclimate</u>

twp temporary water market price (\$/ML)

w_{a}^{t} irrigation water requirements for annual pastures in season t (ML/ha)

w_{p}^{t} irrigation water requirements for perennial pastures in season t (ML/ha)

p_{f} price of feed grain (\$/tonne)

p_{h} price of bought-in hay (\$/tonne)

<u>Fixed parameters</u>

p_{w} delivery price of water (\$/ML)

p_{c} price of cutting and storing farm-grown hay (\$/ha)

O cost of oversowing 1 ha of perennial pasture (\$/ha)

O_{a} cost of converting 1 ha of perennial pasture to annual pasture (\$/ha)

O_{p} cost of oversowing 1 ha of annual pasture to perennial pasture (\$/ha)

AP maximum area of annual pasture available for irrigation (ha)

PP maximum area of perennial pasture available for irrigation (ha)

MJ^{t} energy requirements in season t (MJ)

P^{t} protein requirements in season t (% DM)

F^{t} fibre requirements in season t (% DM)

D minimum density (MJ/tonne DM)

DM_a^t pasture accumulation for annual pastures in season t (tonnes DM/hectare)

DM_p^t pasture accumulation for perennial pastures in season t (tonnes DM/hectare)

DM_f tonnes DM per tonne feed grain

DM_h tonnes DM per tonne hay

MJ_a MJ per tonne DM, pastures

MJ_f MJ per tonne DM, feed grain

MJ_h MJ per tonne DM, hay

P_a^t protein in pastures, season t (% DM)

P_f protein, feed grain (% DM)

P_h protein, hay (% DM)

F_a^t fibre in pastures, season t (% DM)

F_f fibre, feed grain(% DM)

F_h fibre, hay (% DM)

Appendix 2: Data

Parameter	Value	Source	Comments
twp	\$50-\$750/ML		Changes with the hydroclimate
p_w	\$35/ML	Ho *et al.* (2007)	Variable cost of water delivery relatively low. There are also large fixed costs.
p_f	\$180-\$350/t		Changes with the hydroclimate
p_h	\$120-\$350/t		Changes with the hydroclimate
p_c	\$200/ha	Personal communication, Richard Stockdale (DPI)	
O	\$250/ha	Personal communication, DPI	
O_a	\$335/ha	Ho *et al.* (2007)	
O_p	\$272/ha	Ho *et al.* (2007)	
w_a^1	0.34 ML/ha	Average of the 112-yr PRIDE series	For documentation on the PRIDE model, see SKM (1998)
w_a^3	1.9 ML/ha		
w_p^1	1.84 ML/ha		
w_p^2	4.67 ML/ha		
w_p^3	1.63 ML/ha		
AP	0.16 ha, pre-2000 0.08 ha, post-2000		
PP	0.48 ha, pre-2000 0.24 ha, post-2000		
DM_a^1	6 t DM/ha	Experimental data for perennial pastures, from Christie Ho, DPI. Annual pastures, amended by Kerry Greenwood, Victorian DPI.	
DM_a^3	1.5 t DM/ha		
DM_a^4	2 t DM/ha		
DM_p^1	4.24 t DM/ha		
DM_p^2	5.15 t DM/ha		
DM_p^3	3.83 t DM/ha		

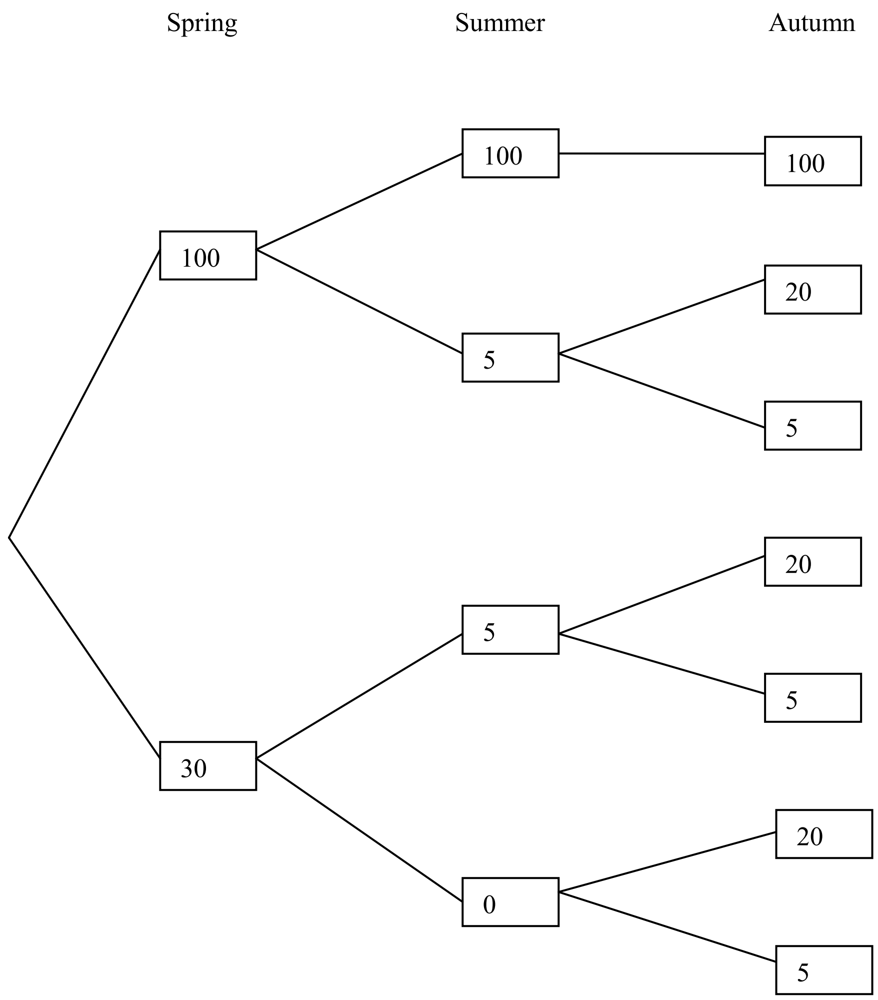
DM_p^4	1.81 t DM/ha		
DM_f	.89 t DM/t	Heard *et al.* (2003)	
DM_h	.88 t DM/t		
MJ_a	10,500 MJ/t	Armstong *et al.* (2000)	
MJ_f	12,500 MJ/t		
MJ_p	9,000 MJ/t		
MJ^1	15,687 MJ	Based on the methodology of Armstong *et al.* (2000), with seasonal milk production data from the Situation and Outlook publications.	
MJ^2	13,973 MJ		
MJ^3	11,014 MJ		
MJ^4	11,647 MJ		
P_a^1	0.24	Dietcheck manual and software (Heard *et al.* 2003)	
P_a^2	0.2		
P_a^3	0.2		
P_a^4	0.25		
P_f	0.11		
P_h	0.18		
P^1	0.185		
P^2	0.165		
P^3	0.15		
P^4	0.12		
F_a^1	0.36		
F_a^2	0.46		
F_a^3	0.44		
F_a^4	0.36		
F_f	0.2		
F_h	0.45		
F^t	0.3	Target 10 (Jacobs and Hargreaves 2002)	
D	10,000 MJ/t DM	Stockdale (2008)	

Appendix 3: Relationship between dry matter production and irrigation

These graphs are based on information very kindly provided by Kerry Greenwood and Alister Lawson of the Victorian DPI.

Perennial pastures

The decision tree below shows diagrammatically the impact on perennial pasture dry matter production in the current and future seasons of choosing not to irrigate. At each timestep, the top branch represents a decision to irrigate, whereas the bottom branch represents a decision not to irrigate (this applies to the figure for annual pastures over the page as well).



The numbers in the box represent the percentage of potential dry matter resulting from current and past decisions. These percentages apply for relatively dry seasonal conditions: in wet seasonal conditions, dryland pasture accumulation would be closer to irrigated pasture accumulation. It is assumed that pastures have been well irrigated previously.

Annual pastures

As in Appendix 3, this decision tree represents the implications of choosing not to irrigate on dry matter accumulation for annual pastures. Again, dry seasonal conditions are assumed, and the top branch represents a decision to irrigate.