36th Annual Conference of the

Australian Agricultural Economics Society

Australian National University, 10-12 February 1992

Canberra ACT, Australia

Optimising the Cow Culling Decision in Beef Herds

R.J. Farquharson

NSW Agriculture

Agricultural Research and Advisory Station

Private Mail Bag

Grafton NSW 2460

Farm management decisions on alternative beef cow culling and replacement policies and the best age to cull cows under alternative policies involve both economic and biological factors. As cows increase in age their biological performance increases, plateaus and then declines and annual costs increase. An implication of this is that if profits are to be maximised in a whole-herd context then there is an optimum age to cull and replace cows for alternative culling policies.

A biological performance dataset for beef cows of different breeds up to 16 years of age is currently being finalised. The aim of this paper was to review previous studies of this question and to investigate two mathematical programming approaches (linear and dynamic programming) to the solution. A preliminary analysis using these methods is presented.

1. Introduction

The questions of what is the best cow culling and replacement policy and what age to cull and replace breeding cows in commercial beef herds involve a number of factors. These include the biological performance and annual costs of both breeding cows and heifer replacements over their remaining lifetimes, the capital cost of replacements and the salvage value of cull cows. The biological performance of the beef cow varies between cow age groups (over the animal's lifetime). Cows could conceivably be kept up to 16 years of age or older, but at some point their animal production performance begins to decline and/or costs rise. The implication from this is that there is an optimum age to cull herd cows and substitute replacements.

The farm management decision on how and when to cull must be taken in a whole-herd context - it is the combined decision on at what age to cull and how many replacements need to be substituted to achieve a desired herd size that is important. The underlying rationale for this question is that in commercial beef production, managers are interested in maximising profits so the opportunity costs of keeping a cow are important.

The aim of the research associated with this paper is to conduct a farm management oriented analysis to compare alternative cow culling policies and determine the optimum age to cull and replace cows for each policy in beef herds of different breeds. It will also aim to provide information on the sensitivity of profits to moving away from the optimum cow culling policy and culling age, and on the breakeven prices affecting the breed/buy female replacements and the cull/keep cow decisions.

In this paper the focus is mainly on discussing alternative analytical options for determining an optimum culling strategy. The approach is to investigate some quantitative methods using a preliminary data set. Section 2 of the paper contains a discussion of alternative culling strategies in commercial beef herds. Section 3 contains a review of literature on this question including analytical approaches used in other studies. Following that the information from the biological research is described in Section 4 and some results presented in Section 5. The final section includes discussion of the results and some implications.

2. The problem

In commercial beef production, cows may be culled involuntarily (due to death or health reasons such as eye cancer) or voluntarily for performance (according to teeth failure, reproductive performance or the need to achieve genetic improvements).

In any year the possible reproductive outcomes are that cows may not calve, may calve and not wean or may calve and wean. The types of costs incurred in keeping a cow that does not wean a calf include feed and cash. The maintenance feed requirements of a cow are often asserted to be about 70% of total intake, so there are substantial costs involved in keeping a cow that does not wean a calf. That feed could have been used for a replacement (pregnant) cow. The return from the replacement cow is part of the opportunity cost of keeping the non-pregnant cow .

Given these three reproductive outcomes a number of performance (voluntary) culling and replacement policies can be formulated. In increasing order of stringency on cow performance some of these policies are :

1. Cull if cow does not calve in 2 consecutive years;
2. Cull if cow does not calve and wean in 2 consecutive years;
3. Cull if cow does not calve in any year; and
4. Cull if cow does not calve and wean in any year.

In practice there is generally only a small loss between calving and weaning and beef managers base their culling decisions on calving rather than weaning (ie policies 1 and 3).

In the temperate regions of Australia a typical performance culling policy is to check the teeth of cows in autumn (at weaning) and cull cows accordingly. Apart from teeth, cows are generally culled in the higher rainfall areas if they miss one calf, however young cows having their second calf might be allowed to miss one calf in that year. Therefore a further performance culling policy might be :

2A. Cull if cow does not calve in any year apart from that of her second calf.

The problem then is to determine the optimum culling policy if herd profit is to maximised assuming that no genetic gain is being pursued through selection for superior genetic merit. What is the financial outcome for each of the five possible culling policies if the feed supply is limiting? And what is the optimum age to cull and replace cows under each culling policy for different breeds and different pasture types? These are the questions to which the analysis reported in this paper could be addressed.

A number of considerations influence the outcome of these questions. One of these is that the analysis needs to be done in a whole herd context so that the culling decision is determined in conjunction with the number of replacements required to maintain the herd size according to the overall farm management goal. There is also the related question of whether the replacement females should be purchased or bred from the herd. This question is perhaps primarily economic (comparative cost and performance of replacement females) although the availability and quality of replacements is a concern for beef managers. A further economic issue is what happens to the optimum culling age if the price relativities between progeny, cull cows and replacements change.

Another factor impinging on the two questions above is whether herd size can change. Two alternative scenarios could be considered. One is a relatively static analysis where beef prices and price relativities do not change and where herd size (or, more strictly, feed supply) is fixed. This could relate to a property where beef production is the only activity or enterprise and a 'rule of thumb' is required for culling at current prices. The second scenario could be a more dynamic case where both price relativities (beef progeny versus culls and beef relative to other commodities) and the herd size can vary. This scenario might relate to a mixed-enterprise property where the size of the beef activity could change at the expense of other activities.

The analysis of the two questions above should ideally incorporate stochasticity in important parameters if this is substantially different between culling strategies and might affect the outcomes. The ability to answer these questions for the case of genetic improvement would also be useful for farm managers.

3. Analytical approaches

Research has been conducted into the issues of beef cow lifetime production performance, culling policies and the optimum culling age for cows. A number of different questions have been posed and the analytical methods used have been selected accordingly. Issues of both a biological and an economic nature have been addressed.

One approach to comparative lifetime production has been to look at cow longevity (eg Bailey (1990), Nunez-Dominquez et al. (1991) and Arthur et al. (1992)) and lifetime productivity (eg Newman et al. (1992), Nunez-Dominquez et al. (1991), Arthur et al. (1992) and Hearnshaw et al. (1985)). There are also reports on the reasons for disposal of cows (eg Arthur et al. (1992), and

Hearnshaw et al. (1985)). In these analyses measures of survival rates, culling and weaning rates, weaning weight and cow size are derived for different breeds.

Chisholm (1966), Burt (1965) and Perrin (1972) developed a general model of asset replacement to provide criteria defining opportunity costs appropriate for the asset replacement decision. These principles were based on maximising Net Present Value (NPV) and equating marginal revenues with marginal opportunity costs. These replacement policies were for any type of asset which could be self-replaced or replaced by a technologically-improved asset. Trapp (1986) applied those principles to beef cow culling and replacement strategies in the US where cattle prices vary cyclically and herd sizes were allowed to change.

Melton (1980) expanded the work of Perrin (1972) by the inclusion of animal breeding principles in the culling and replacement decision to achieve genetic progress in a beef herd breeding its own female replacements. The effect of aiming for genetic technological progress was to reduce the optimal replacement age according to the size of the annualised economic value of genetic progress.

A number of authors have used Dynamic Programming (DP) to determine optimal culling policies primarily in dairy cows (eg McArthur (1973, 1975), Stewart et al. (1978), Stewart et al. (1978), Van Arendonk (1985, 1986) and Dijkhuisen et al. (1985)). DP is 'a mathematical technique which divides a multi-stage problem into a series of independently soluble single-stage problems' (Stewart et al. 1978, p. 603). Over a long term planning horizon the DP model determines the optimal culling policy for all possible states (incorporating probabilities and outcomes) in all years using a recursive relationship and determines the optimal (profit maximising) policy. The DP approach can incorporate probability statements for each state in each year of the solution. One problem with this approach is that there may be a large number of state variables that have to be specified. McArthur (1973) used this approach to compare profits for herds operated under different culling strategies to determine the value of culling for genetic merit.

More recently Azzam et al. (1990) have used Markov chains as a shortcut method to estimate age distributions in herds of beef cattle under different culling strategies. They used age-specific probabilities for health and reproductive failure to obtain age distributions in herds under different culling strategies. The culling process was described as a Markov chain. The results of this type of analysis can be used as an input to economic analysis and simulation studies.

Simulation has also been used to evaluate culling strategies and management systems. Bourdon and Brinks (1987) used a modified version of the Texas A & M Beef Cattle Production Model to simulate life-cycle biological and economic efficiency of various culling strategies and management systems. Clarke et al. (1984) used mathematical modelling to evaluate the economic efficiency of various management practices including culling at different ages. Congleton and Goodwill (1980) used a dynamic model of a beef cow herd producing feeder calves to simulate different culling policies for seven breeds. Their results showed the effects of different culling strategies on the structure and productivity of the herds.

The development of an expert system to combine biological and economic information was undertaken by Oltjen et al. (1990) to make recommendations on whether to keep or cull commercial beef cows. Biological information on the cow was combined with a NPV based on the cow's expected future performance and salvage value to come up with a recommendation (keep or cull) for each cow.

Linear Programming (LP) is another analytical method that can be used in optimising studies. Ladd and Gibson (1978) used this method to analyse the potential impact of technological change at the farm level. In their application the LP results were for use at the project planning stage to influence the choice of technical changes developed for the future.

Dent et al. (1986) exposited the use of LP as a planning tool where the farm management problem is expressed as three elements - a set of objectives, a range of possible activities or enterprises and a set of limited resource supplies or other constraints. 'The optimal farm plan is that combination of activities that best fulfils the objectives of the farmer and is feasible in terms of the constraints' (Dent et al. 1986, p. 2). This is achieved by optimising the value of the objective function (eg maximising the value of total herd gross margin) after accounting for the opportunity costs of each activity. Dent et al. (1986) provide a number of examples of more complex applications of LP in farm planning. Two of these involve livestock reconciliation and determining the optimal culling age.

3.1 A Linear Programming Aproach

An LP approach to optimising the age to cull beef breeding cows would involve having separate activities for each cow age group. Within each activity the productivity measures of death percentage, calf weaning rate, progeny weaning weights and cow weights could be specified. Other activities would include progeny sale and options of selling cows at any age. The required number of female replacements would be determined within the solution and an option of buying replacements could be included. The feed requirements of cows in each age group could be determined according to liveweight and other factors and a fixed feed supply set as a constraint within the model matrix. The objective would be to maximise profits on a whole-herd basis (including the sale of progeny and culled cows).

The results of LP models include the levels of activities in the optimal solution. Information is derived on the amount that the objective function would decrease if one unit of an activity not in the optimal solution was to be forced into the farm plan. The LP solution also shows whether the constraints in the model (eg feed or labour supply) are binding or slack. A shadow price is computed for each constraint that is binding. This shows how much the value of the objective function would increase if one more unit of the resource forming the constraint were available, provided that nothing else is changed in the model (ie *ceteris paribus*). Other economic information is also generated in the LP output.

The performance measures of cows will be affected by the culling strategy used. If biological information is available on cow performance under different culling strategies, then an LP analysis could be conducted for each strategy using the relevant figures. A separate model would be solved for each case and the economic comparisons made. An example of the LP analysis for one breed x nutrition x culling strategy is shown in Section 5.

3.2 A Dynamic Programming Approach

McArthur (1975) categorised a herd or flock as a continuous production enterprise in which a whole series of decisions about replacing animals has to be made. The sequence of decisions over time constitutes a replacement policy. Such replacement problems can be solved using DP.

There are a number of components of a DP problem (Lee, Moore and Taylor 1985):

(i) a <u>stage</u> - the problem can be decomposed into smaller sub-problems or stages (denoted by n) which are numbered from the last to the first to indicate the number of remaining decision points. An important question is the length of the planning horizon for the decision-maker;

(ii) a state - the system status or state represents the linkage or informaton flow between stages. There may be a number of states within each stage. If i_n denotes each state in stage n, then $i_4 = 6$ represents the decision about replacement of a six-year old animal in stage 4;

(iii) a decision - the decision variable (D_n) represents the possible alternative actions at each stage. For stock replacement, alternative decisions might be to cull or keep the female;

(iv) a transition function - describes how the stages of the problem are interconnected by defining, via a functional relationship, the value the state variable will have at each stage. Alternative replacement policies could be defined by different transition functions;

(v) stage returns - the symbolic representation of the return (profit, cost, utility, etc) at each stage. The return is a function of both the state and decision variables symbolised by R_n. For instance $R_6(3_6,1_6)$ might indicate the revenue with five years to go from a three year old animal where the decision is to keep her (ie D = 1);

(vi) stage optimisation - is the determination of the optimal decision at each stage for each possible input state variable. Generally at each stage the optimal solutions ($f_n(i_n)$) must be found for each possible level of the state variable. Thus ($f_n(i_n)$) is the value of being in the nth stage and the ith state when following a policy laid down by the set of decisions for this and following stages in the policy or transition function.

The recursive return function of DP is represented as:

$$f_n(i_n,D_n) = R_n + f_{n-1}(i_{n-1},D_{n-1})$$

This means that the total accumulated return at (and including) stage n (given the input to stage n and the decision at stage n) is equal to the stage n return plus the optimal return at stage n-1 (Lee, Moore and Taylor 1985, p. 619).

Generally this means that the optimal value of a particular (state) class of animal with n years before termination is equal to the value of the best decision, which is composed of the immediate return from the animal given that decision, and the value of following the optimal replacement subsequently (McArthur 1975). A number of validity conditions are required for this relationship to hold.

3.3 Comparison of methods

The biological information available for this analysis consists of age-specific performance data for beef cows of different breeds and in different levels of pasture nutrition. The data used will be described more fully in the next section. This information should enable an analysis of culling strategies using both LP and DP. Slightly different information could emanate from each type of analysis. For instance more specific shadow price information could emerge from the LP analysis. Both methods should arrive at the same optimal strategy.

DP should incorporate analysis of all policies or strategies in one model, whereas LP will require separate models for each culling strategy. An example of an LP result is presented in Section 5, but the DP analysis has not yet been undertaken.

4. Materials and method

4.1 Breeds and nutrition

The information used in this analysis comes mainly from a long-term beef cattle crossbreeding project conducted at Grafton, New South Wales, from 1972 to 1990 (Barlow et al. 1989). Cattle were evaluated on three levels of pasture nutrition termed High, Medium and Low (Barlow et al. 1989). The breeding systems evaluated included four dam genotypes (Hereford (HH), Brahman-Hereford (BH), Simmental-Hereford (SH) and Friesian-Hereford (FH) and one sire breed (Hereford (H)). Consequently the breeding systems analysed included those producing straightbred Hereford and back-cross calves as shown in Table 1

Table 1

Experimental Factors In Crossbreeding Project

Sire Breed	Dam Breed	Breeding System	Nutrition Level
Hereford (H)	Hereford (HH)	HxHH	
	Brahman-Hereford (BH)	HxBH	High
	Simmental-Hereford (SH)	HxSH	Medium
	Friesian-Hereford (FH)	HxFH	Low

4.3 Biological data

The performance of cows has been measured from this project for age groups up to 16 years. The important biological partial productivity measures used in this analysis are calving percentage, weaning percentage, weaning weight of progeny, cow weight and cow death percentage. Preliminary data for the Hereford system on Medium nutrition are in Table 2.

4.4 Culling Policy

In determining the cow performance culling policy (ie voluntary culling) three reproductive outcomes are possible in any year. A cow might calve and wean, calve and not wean or not calve. Cows that calve and not wean might have had stillborn calves, the calves may have died neo-natally (within 48 hours of birth) or they may have died post-natally (after 48 hours from birth).

The performance culling policy used within the project was that cows were culled on High and Medium pastures after two consecutive years of non-calving and on Low pastures after three consecutive years of non-calving. Industry practice for cow performance culling in Australia varies widely, but is probably more strict than the above policy (ie cull after less non-calvings) in more intensively managed regions.

The performance measures of cows will be affected by the culling strategy used. However, it is possible to adjust the performance measures to a more strict culling basis by deleting the records of cows that, for instance, were not pregnant in the second year. Although this will reduce the number of records available, it will allow an assessment of the gain from changing culling strategies.

The measure of cow weight is included to estimate feed demand. In a farm management context the pasture feed supply may be considered relatively fixed. The feed requirements of cows can be estimated in terms of Metabolisable Energy (ME) units. Factors influencing ME requirements are animal liveweight and age, exercise, feed quality, level of feeding (whether for maintenance, weight gain or weight loss), gestation and lactation (Rickards and Passmore 1977, Agricultural Research Council 1980, Ministry of Agriculture, Fisheries and Food 1984, Animal Production Committee 1990). The ME requirements were estimated for spring calving herds at weaning.

Table 2

Preliminary Productivity measues: Hereford Cows on Medium nutrition

Cow age groups	Calving percentage	Weaning percentage	Weaning weight Steers	Weaning weight Heifers	Cow weight	Cow death percentage
years	%	%	kg	kg	kg	%
2			183	165	307	1.5
3	74	68	208	197	354	0.5
4	90	81	232	216	370	0.8
5	89	82	250	232	396	0.8
6	100	89	247	246	408	0.3
7	81	77	254	235	410	2
8	91	87	250	238	412	0.8
9	81	76	265	250	417	1.5
10	79	74	249	252	433	1.5
11	81	75	276	222	431	2
12	90	80	249	239	431	1
13	38	38	240	252	402	2
14	80	80	252		414	1.5
15				214	405	0.5
16					436	0.8

To compare different cow breeds (with different body weights) within the LP model approach a fixed amount of feed was allocated. Comparisons of financial returns between breeding systems within pasture types are possible by adjusting the cow numbers for differences in cow weight given a fixed feed supply.

5. Results

An LP analysis of the preliminary dataset for one breed and nutrition combination was undertaken and the results are presented here. The LP model structure was derived from that of Dent et al. (1986, Chapter 6). The model activities included cows aged from 2 to 16 years, options to breed or buy replacement heifers, selling activities for steer and heifer calves at weaning from cows aged from 2 to 16 years, and selling cows at any age. The cow activities incorporated weaning percentages for each cow age. Sale prices and variable costs were derived from farm budget handbooks.

Model constraints included feed in ME units. Feed requirements for each cow age group and progeny type were generated. Tie rows were used to transfer cows between age groups (after accounting for death rates at each age) or to the cow sale activities at any age. Female calf tie rows transferred calves back into the herd via heifer replacements or to the heifer sale activities. Male calf tie rows transferred calves into the steer sale activities.

The objective function was profit maximisation. The annual cash costs of each cow age group were inserted in the objective function, as were the cost of purchased heifer replacements and the net proceeds of sales of steers, surplus heifers and culled cows.

This matrix was solved using LP88 (Eastern Software Products 1987) and the results are shown in Table 3. The value of objective function was $21538. The basic variables in the optimal solution are shown. The herd consisted of 143 cows (including heifer replacements) and cows were culled and sold after their 8th calf. Steers were sold from each cow age group.

The activity buying female replacements was included in the LP matrix with an objective function value of -$360. This was obviously too much to pay because the 16.6 heifer replacements were derived from the heifer calves of the 3 year old cows (5.5 heifers), 4 year old cows (6.5 heifers) and the 5 year old cows (4.6 heifers). The imputed value for the activity buying heifer replacements was -$251. At prices below this level it is more profitable to buy replacements than breed them.

6. Discussion

The LP results presented in the previous section are preliminary, they are presented as an illustration of how the problem can be set up and solved. The LP matrix used is available from the author. Further refinement of this model will be undertaken.

The results presented are close to industry practice, which should not be surprising. Those results reflect the culling policy used in the research experiment. If the research dataset is able to be refined, cow performance measures for stricter culling policies will be derived and solved to determine any financial advantage or change in optimum culling age. The LP model will be set up and solved for other breeding system and pasture productivity combinations.

One problem with the LP88 package is its inability to read 'large' matrixes from a data file. The LP matrix here was only 74 columns by 46 rows, but the program would not read it from a file. To undertake a duplicated analysis for a number of options is not efficient if all matrixes must be individually keyed in. A better package is required and GAMS (Brooke, Kendrick and Meeraus 1988) has been considered. Ideally the DP analysis should be undertaken with the same program, but further consideration is required of the best program to use.

Table 3

Linear Pragramming Results

Basic Variables	Value	Basic Variables	Value
Heifer replacements	16.6	Sell steers 6 YO cows	7
2 Year old cows	16.3	Sell steers 7 YO cows	6
3 Year old cows	16.1	Sell steers 8 YO cows	6.7
4 Year old cows	16	Sell steers 9 YO cows	5.8
5 Year old cows	15.9	Sell heifers 2 YO cows	5.6
6 Year old cows	15.7	Sell heifers 5 YO cows	1.9
7 Year old cows	15.7	Sell heifers 6 YO cows	7
8 Year old cows	15.4	Sell heifers 7 YO cows	6
9 Year old cows	15.3	Sell heifers 8 YO cows	6.7
Sell cows after 8 calves	15	Sell heifers 9 YO cows	6.7
Sell steers 2 YO cows	5.6	Heif. Repl. 3 YO cows	5.5
Sell steers 3 YO cows	5.5	Heif. Repl. 4 YO cows	6.5
Sell steers 4 YO cows	6.5	Heif. Repl. 5 YO cows	4.6
Sell steers 5 YO cows	6.5	Objective Function	$21538

References

Agricultural Research Council (1980), *The Nutrient Requirements of Ruminant Livestock*, Commonwealth Agricultural Bureaux, Farnham Royal.

Animal Production Committee (1990), 'Feeding Standards for Australian Livestock, Ruminants', edited by J.L. Corbett, CSIRO, East Melbourne.

Arthur, P.F., Makarechian, M., Berg, R.T. and Weingardt, R. (1992), 'Longevity and Lifetime Productivity of Range Beef Cows', In preparation.

Azzam, S.M., Azzam, A.M., Neilson, M.K. and Kinder, J.E. (1990), 'Markov Chains as a Shortcut Method to Estimate Age Distributions in Herds of Beef Cattle Under Different Culling Strategies', *Journal of Animal Science* 68:5-14.

Bailey, C.M. (1990), 'Longevity of Bos Taurus and Bos Taurus x Bos Indicus breed types in a dry, temperate climate', 4th World Congress on Genetics Applied to Livestock Production, Vol. 14, 327-30, Edinburgh, Scotland.

Barlow, R., Farquharson, R. and Hearnshaw, H. (1989), 'Profit from Planned Crossbreeding', Agricultural Research and Advisory Station, Grafton, NSW.

Bourdon, R.M. and Brinks, J.S. (1987), 'Simulated Efficiency of Range Beef Production. 3. Culling Strategies and Nontraditional Management Systems', *Journal of Animal Science* 65:963-69.

Brooke, A., Kendrick, D. and Meeraus, A. (1988), 'GAMS: A User's Guide', The Scientific Press.

Burt, O.R. (1965), 'Optimal Replacement Under Risk', *Journal of Farm Economics* 47:60-7.

Chisholm, A.H. (1966), 'Criteria for Determining the Optimum Replacement Pattern', *American Journal of Agricultural Economics* 48:107-12.

Clarke, S.E., Gaskins, C.T., Hillers, J.K. and Hohenboken, W.D. (1984), 'Mathematical Modelling of Iterative Culling and Crossbreeding Strategies in Beef Production', *Journal of Animal Science* 58(1):6-14.

Congleton, W.R. and Goodwill, R.E. (1980), 'Simulated Comparisons of Breeding Plans for Beef Production: Part 3 - Systems for Producing Feeder-Calves Involving Intensive Culling and Additional Breeds of Sire', *Agricultural Systems* 5:309-18.

Dent, J.B., Harrison, S.R. and Woodford, K.B. (1986), *Farm Planning with Linear Programming: Concept and Practice*, Butterworths, Sydney.

Dijkhuizen, A.A., Renkema, J.A. and Stelwagen, J. (1985), 'Economic Aspects of Reproductive Failure in Dairy Cattle. 2. The Decision to Replace Animals', *Preventative Veterinary Medicine* 3:265-76.

Eastern Software Products (1987), 'Linear Programming for the IBM PC, LP88 User's Manual', Alexandria, Virginia.

Hearnshaw, H., Darnell, R. and Barlow, R. (1985), 'Effect of breed on cow wastage', Proceedings of 5th Conference of AAABG, Sydney.

Ladd, G.W. and Gibson,C. (1978), 'Microeconomics of Technical Change: What's a Better Animal Worth?', *American Journal of Agricultural Economics* 60(2):236-40.

Lee, S.M., Moore, L.J. and Taylor, B.W. (1985), *Management Science*, 2nd edn, W.C. Brown, Dubuque, Iowa.

McArthur, A.T.G. (1973), 'Application of Dynamic Programming to the Culling Decision in Dairy Cattle', Proceedings of the New Zealand Society of Animal Production, Vol. 33, Massey University, Palmerston North.

__________ (1975), 'Dynamic Programming applied to animal replacement decisions', Unpublished Ph.D thesis, University of Canterbury, Lincoln College.

Melton, B.E. (1980), 'Economics of Beef Cow Culling and Replacement Decisions Under Genetic Progress', *Western Journal of Agricultural Economics* 137-47.

Ministry of Agriculture, Fisheries and Food (1984), 'Energy allowances and feeding systems for ruminants', 2nd edn, Reference Book 433, HMSO, London.

Newman, S., Stewart, T.S. and Deland, M.P. (1992), 'Lifetime Productivity of Crossbred Cows. III. Cow survival, optimal mature cow size, lifetime productivity', *Australian Journal of Experimental Agriculture* (submitted).

Nunez-Dominquez, R., Cundiff, L.V., Dickerson, G.E., Gregory, K.E. and Koch, R.M. (1991), 'Lifetime Production of Beef Heifers Calving First at Two vs Three Years of Age', *Journal of Animal Science* 69:3467-79.

Oltjen, J.W., Selk, G.E., Burditt, L.G. and Plant, R.E. (1990), 'Integrated Expert System for Culling Management of Beef Cows', *Computers and Electronics in Agriculture* 4:333-41.

Perrin, R.K. (1972), 'Asset Replacement Principles', *American Journal of Agricultural Economics* 54: 60-7.

Rickards, P.A. and Passmore, A.L. (1977), 'Planning for profit in livestock grazing systems', Professional Farm Management Guide Book No. 7, ABRI, University of New England, Armidale.

Stewart, H.M., Burnside, E.B. and Pfeiffer, W.C. (1978), 'Optimal Culling Strategies for Dairy Cows of Different Breeeds', *Journal of Dairy Science* 61(4): 1605-15.

Stewart, H.M., Burnside, E.B., Wilton, J.W. and Pfeiffer, W.C. (1978), 'A Dynamic Programming Approach to Culling Decisions in Commercial Dairy Herds', *Journal of Dairy Science* 60(4): 602-17.

Trapp, J.N. (1986), 'Investment and Disinvestment Principles with Nonconstant Prices and Varying Firm Size Applied to Beef-Breeding Herds', *American Journal of Agricultural Economics* 68(3):691-703.

Van Arendonk, J.A.M. (1985), 'Studies on the Replacement Policies in Dairy Cattle. 2. Optimum Policy and Influence of Changes in Production and Prices', *Livestock Production Science* 13: 101-21.

________________ (1986), 'Economic Importance and Possibilities for Improvement of Dairy Cow Herd Life', 3rd World Congress on Genetics Applied to Livestock Production.