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EVALUATING REPRODUCTIVE MANAGEMENT CHANGES IN A DAIRY HERD: EFFECTS OF LACTATION CURVE SPECIFICATION

By

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ABSTRACT

EVALUATING REPRODUCTIVE MANAGEMENT CHANGES IN A DAIRY HERD: EFFECTS OF LACTATION CURVE SPECIFICATION

By

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An economic model was developed to evaluate reproductive management decisions for a dairy farm. The model includes opportunity costs of management labor, capital, and changes in herd structure associated with reproductive performance improvements. The reproductive analysis was conducted using alternative lactation curve specifications to examine the influence of lactation curve specification on reproductive management decisions. Four common lactation curve models were fitted to daily milk yield data from a dairy herd, pooled by parity and season of calving. Nonlinear models showed higher R^2 and lower root mean square error than the Wood models, particularly for cow lactations. Despite fit differences, all lactation curve models showed identical reproductive management decision results. Scenario values assessed using the Wood models were consistently lower than both the nonlinear models. Changes in labor and replacement costs were larger than the changes in milk income over feed costs for all lactation curve models.

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INTRODUCTION

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1.1.1 What is reproductive performance?

Reproduction is essential to milk production. All cows must maintain a continuous reproductive cycle to keep producing milk at an economically viable level. Continuity of the reproductive cycle is maintained by establishing and sustaining a pregnancy during lactation; calving begins a subsequent lactation. Reproductive performance is the degree of success in accomplishing pregnancy rapidly after each calving. Reproductive performance can be measured with average pregnancy rate, the proportion of nonpregnant cows that become pregnant in each estrous cycle. Pregnancy is accomplished in two steps—estrus[1] must be detected and a successful breeding must take place. The estrus detection rate (EDR) is the proportion of nonpregnant cows that are correctly determined to be in estrus (and bred) in each estrous cycle[2]. The conception rate (CR) is the proportion of cows bred in each estrous cycle that become pregnant. The pregnancy rate is the multiplicative product of the success rates of these two steps.

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[1] Estrus is the period of sexual receptivity that occurs at the beginning of each estrous cycle. Estrus typically occurs every 18-24 days and last 12-24 hours. Ovulation occurs during estrus and is the only time during the estrous cycle when conception can result from a breeding (Senger, 1997).

[2] In this thesis, the estrus detection rate applies only to cows eligible for breeding by meeting any requirement for minimum days to first service. Further, all cows detected in estrus are assumed to be bred. Thus, the estrus detection rate is identical to the breeding rate.

The pregnancy rate(s) in the herd defines the calving interval distribution across cows in the herd. The calving interval is the length of time between a cow's successive calvings. Higher levels of reproductive performance result in shorter calving intervals. The calving interval can be voluntarily extended by delaying the first breeding. The biological minimum calving interval in most herds is 12 months. Calving intervals of 18 months or more can be considered relative reproductive failure.

1.1.2 Reproductive performance is important to profitability

Improving reproductive performance influences herd profitability by increasing the frequency of calving (inversely, the calving interval), affecting both net income and labor allocation. Shorter calving intervals are associated with additional calves born each year, increased milk yield, and a decrease in cows culled and replaced due to reproductive failure. Thus, revenues for milk and calves and feed, labor, and veterinary expenses are all increased and culling revenues and replacement costs decreased by reproductive performance improvements. The change in labor requirements for estrus detection, breeding, and herd health is also a significant economic consideration. Estrus detection, breeding, and herd health all require management and (or) skilled labor, which are typically limited on farms and thus have high opportunity costs.

The dairy science literature has traditionally indicated that that short calving intervals (~13 months) are higher in value than their longer counterparts because cows spend a larger proportion of their lifetime in peak production (Holmann et al., 1984; Schmidt, 1989). Estimated losses associated with low reproductive performance are significant.

Estrus detection failure was estimated to cost the dairy industry $300 million annually in 1994 (Senger). Plazier et al. (1997) valued a one percent improvement in estrus detection rate at $22.50 per cow. Using a partial budget model, Hady et al. (1994) reported that comprehensive improvements in reproductive performance for a 300 cow Michigan dairy herd could increase net income up to $18,485. Schmidt (1989) estimated that reducing the calving interval from 14 months to 13 months would increase income over feed and variable costs by up to $21.50 per cow.

1.1.3 Reproductive performance is on the decline

Statistics indicate that calving intervals have been, on average, increasing. Calving intervals in the mid-1980s averaged 13.5 months but now approach 15 months (Lucy, 2001). A combination of reasons has been suggested for these findings. In the dairy science literature, the most common explanation is decline in fertility associated with high levels of milk production (Lucy, 2001; Stevenson, 2001).

Management choices due to economic considerations, too, likely play a part in this phenomenon. One critical decision is the allocation of scarce farm resources to reproductive management activities. Reproductive management requires significant amounts of labor and capital, both of which are increasingly scarce resources for a farm. Allocation of these resources to reproductive activities is intricately tied to reproductive performance. Thus, allocating these resources to other enterprises on the farm and (or) activities in the dairy enterprise is limiting to reproductive performance. Some producers voluntarily reduce their allocation of labor to reproductive activities in order to reduce the labor requirements of the dairy herd. Recent popular press articles indicate that the cost of voluntarily extending the calving interval may be reduced in herds using bST, due to high milk yield persistency (Galton, 1997; Roenfeldt, 1996).

1.2 Herd reproductive management decisions

The methods that a dairy farm currently employs to accomplish pregnancy define the herd "reproductive management system." A specific reproductive management system can be associated with a particular level of reproductive performance. The managerial decision is whether or not to change the current herd reproductive system. The decision involves an assessment of the benefits of improving reproductive performance and the costs of implementing the change.

The most common decision is whether to change estrus detection to improve reproductive performance and (or) reduce labor requirements. Daily allocation of skilled labor is important to successful estrus detection (Fogwell, 1998). Thus, management labor is often allocated for its accomplishment. Visual estrus detection by management labor can be replaced with hired labor. Because the skill level of hired labor is often lower than management, hired labor usually accomplishes a much lower success rate than management with the same allocation of time.

The labor required to improve reproductive performance, especially estrus detection, can be partially replaced with capital. Technology options to improve reproductive performance and save labor have proliferated (Nebel and Jobst, 1998; Senger, 1994; Stevenson, 2001). Timed breeding protocols (e.g., Ovsynch) synchronize estrus such that successful breeding can be accomplished without visual observation. Mechanical estrus detection systems (e.g., HeatWatch) replace visual observation with pressure sensors mounted on the cow to detect signs of estrus.

1.2.1 Evaluating reproductive management decisions

Because wide variation exists among estimates of the value of improving reproductive performance, it is critical that individual farms evaluate their specific reproductive management decisions using the farm's data. Simulation studies have found the "value of a day open"[3] to be \$0.10 per cow to \$3.00 per cow (Holmann et al., 1984; Plaizier et al., 1998; Schmidt, 1989). Some recent studies have indicated the possibility of positive values to extending the calving interval for some cows – reducing reproductive performance (Jones, 2000; Van Amburgh et al., 1997; Van Arendonk and Dijkhuizen, 1985). Jones (2000) concluded that this scenario was unlikely to be profitable for cows with normal milk yield patterns. Reproductive simulation analyses indicate that the value of improving reproductive performance varies with herd factors, including replacement costs, feeding systems, and seasonal variation in milk production (James and Esslemont, 1979; Schmidt, 1989; Van Arendonk and Dijkhuizen, 1985).

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[3] The "value of a day open", a common concept in the dairy science literature, can be defined as the additional value to be gained when the calving interval is shortened by one day.

The manager's decision to implement a reproductive technology depends upon the benefits of the improvement in reproductive performance relative to the costs of the new management system. Benefits of improved reproductive performance include increased milk production and calf sales, combined with decreased forced replacement and breeding needs. Costs include the labor and supplies (e.g., pharmaceuticals) required to attain the improvement, as well as increased fresh cow costs associated with more frequent calving and feed costs to support additional milk production.

1.2.2 Opportunity costs of reproductive management decisions

In addition to these changes in income and costs, reproductive management decision analysis presents additional challenges in assessing the opportunity costs. Opportunity costs are created when use of a resource in one activity precludes its use for another. Reproductive management decisions involve traditional opportunity costs of labor and capital. In addition, changes in reproductive performance across a herd create opportunity costs in changing the herd structure.

The opportunity cost of capital is a key economic factor in reproductive decisions. Changing reproductive performance shifts capital use over time. Shortening or extending a calving interval represents a delay in the beginning of the next lactation, the return associated with reproduction in this lactation. Calving intervals of different lengths represent delays of varying lengths. In addition, the returns associated with reproductive management investments implemented today occur over the subsequent years. Incorporating the farm's opportunity cost of capital allows comparison of reproductive investments that change reproductive performance (calving interval lengths) to different degrees with different reinvestment requirements.

The opportunity cost of the management labor, too, is important to reproductive decisions. The cost to other farm enterprises of the using scarce management labor for reproductive activities is difficult to estimate on an individual farm. Incorporation of this value is critical to a reproductive analysis to reflect the value (costs) of an investment that spares (uses) scarce management labor.

Finally, opportunity costs created when reproductive performance of one herd management group is changed at the expense of another must also be considered. For example, if a heifer's calving interval is extended, then her higher-yielding cow lactation is delayed. At the herd level, this means that the herd would become a higher proportion of heifers if heifer calving intervals were systematically extended.

1.3 Projecting milk yields for reproductive analysis

Accurately projecting the milk yield effect of changes in reproductive performance is difficult but may be critical for management decisions that appropriately reflect the economic costs. Changing the length of lactation requires predicting milk yield for a hypothetical situation. Reducing calving interval means that the appropriate portion of the lactation must be removed, and lengthening the calving interval requires that an additional period of lactation be added.

Milk yield ascends rapidly after calving, peaking at 40-70 days after calving. Peak yields may be fleeting or continue on for months, as is common in first lactation. After peak, milk yield declines slowly and progressively through the remainder of lactation. Late lactation milk yield is a key opportunity cost of the decision to reduce the calving interval – it is replaced with early lactation milk yield in the next lactation. Conversely, the opportunity cost of the decision to extend the calving interval is the early lactation milk yield that is replaced by the milk yield at the end of the lengthened lactation. Underpredicting the milk yield in the extended portion of the lactation would overvalue an investment that improves reproductive performance (shortens calving interval). If the farm implemented the investment, it would fail to realize the projected increase in net income for the dairy enterprise.

Across individual cows, persistency of milk yield[4] is key to the value of shortening the calving interval (Jones, 2000; Van Arendonk and Dijkhuizen, 1985). Low persistency of milk yield (rapid decline in yield after peak) is associated with a high value to shortening the calving interval. Highly persistent milk yields can result in a positive value to extending the calving interval (Van Arendonk, 1985; Jones, 2000). These findings have critical implications for the importance of the milk yield characterization in determining the value of changing the calving interval. However, persistency is not specifically defined such that findings can be applied in dairy herds.

[4] Persistency of milk yield refers to the rate of milk yield decline after peak yield. The milk yield of a cow with a highly persistent milk yield declines very slowly.

Lactation curve models used in reproductive simulation studies vary significantly in their depiction of milk yield decline as well. The most common lactation curve model, used reproductive analyses by Hady (1994) and Jones (2000), is the incomplete gamma function proposed by Wood, which assumes proportional decline in milk yield over lactation. In contrast, Van Arendonk (1985) and Olds (1979) use models that assume a linear decline. Each of these shapes lead to a different value of the milk yield change that results from extending or shortening lactation.

An empirical lactation curve can be fit to herd milk yield data for individual farms, especially those with daily milk yield data. The lactation curve model provides structure for assessing the change in milk yield that reflects the unique lactation curve shape of the herd. The Wood model is desirable for this purpose because it has a simple mathematical form that can be estimated using linear regression methods. However, evaluation studies generally indicate that the Wood model is not as accurate as more complicated alternative functions in modeling milk yield over lactation. These studies show the Wood model to result in low r-squared (R^2) values, as well as serially correlated error terms because the the functional form is inconsistent with the actual shape of lactation (Congleton and Everett, 1980; Vargas et al., 2000).

A number of nonlinear models have been recently proposed as alternatives to the Wood model. These models show higher R^2 values and less serial correlation of residuals than the Wood model. However, these models have more complicated mathematical forms that require more sophisticated methods to fit farm data.

1.4 Objectives and overview

1.4.1 Objectives

The objective of this thesis is to develop an evaluation method for herd reproductive management decisions using a feasible lactation curve model suitable for farm analysis. Specifically, this research seeks to accomplish the following objectives:

- develop an evaluation model for herd reproductive management decisions that compares the values of alternative reproductive investments using appropriate economic methods and utilizes input information available in herd production and financial records;

- examine the impact of empirical lactation curve model selection on the results of reproductive management decision analysis by comparing the analytical results using various common lactation curve models; and

- demonstrate the economic and lactation curve model applied to a case farm, evaluating alternative reproductive technologies.

1.4.2 Overview

In this thesis, an economic model is developed to evaluate herd reproductive management decisions using methods that account for opportunity costs of capital and labor. Present values for each lactation, converted to annuity equivalents, place all calving intervals on the basis of annualized returns. The annuity equivalents are then weighted by the herd's calving interval composition to determine the total value of the herd. Comparison of the values for the current herd against the value of alternatives determines the most profitable reproductive management decision.

Four empirical lactation curve models are fitted to the daily milk yield data for a dairy farm – two variations of the Wood model and two nonlinear models. The reproductive analysis is conducted using the results from each lactation curve. Four reproductive management alternatives are considered – two that allocate additional labor to reproduction and two that substitute technology for labor.

Despite differences in estimates of the milk yield effects of the changes in reproductive performance, all lactation curve models yield the same reproductive management decision. Changes in labor and replacement costs exceed the changes in milk income over feed costs for all lactation curve models. Thus, the simpler Wood model is an appropriate choice of empirical lactation curve model for reproductive management decision analysis.

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Chapter 2

EVALUATING CHANGES TO THE HERD REPRODUCTIVE MANAGEMENT SYSTEM

Comparing lactation curve models in proper context requires a reproductive management decision analysis framework. That is, to determine whether the choice of lactation curve model affects analysis results. An appropriate framework for a herd manager evaluating a reproductive management decision compares the values of reproductive performance under the current system and with the proposed change by considering its costs and benefits for the herd, including the opportunity costs of labor and capital of changes in reproductive management. Further, the evaluation must standardize calving interval alternatives in comparable units. Finally, to facilitate farm use, the model must use input information easily derived from common herd records.

This chapter outlines a conceptual and empirical model for evaluating the expected change in herd value associated with specific management change scenarios. In Chapter 4, use of this model is demonstrated on a case herd. The analysis is run using alternative lactation curve specifications in order to evaluate the effect of lactation curve specification on reproductive decision results.

In this model, reproductive management is treated like an investment, with changes in the management system and reproductive performance shifting capital investment and returns over time. The first step in establishing the value of a reproductive management change is determination of the present value and annuity equivalent values for lactations with different calving intervals. Associating a calving interval distribution with the expected level of reproductive performance allows these values to be summed to the total herd value. The reproductive management decision is evaluated by comparing the values of alternative management scenarios against the value of the current herd management.

2.1 Reproductive analysis methods in the literature

2.1.1 The optimal calving interval conundrum

Many studies in the dairy science literature have sought to establish a rule of thumb for the "optimal calving interval". Although studies have established that shorter calving intervals are generally associated with higher income, they provide limited insight into reproductive management decisions. The values in these studies reflect average income over feed and selected variable costs (IOFVC) for individual cows – not the investments and management changes in the herd that must be made to improve the herd reproductive performance.

Louca and Legates (1968) found that 13 month calving interval for heifers and a 12 month calving interval for mature cows[5] maximized milk yield using regression analysis of DHIA data. Follow-up studies reported that income over feed and selected variable costs is also maximized with 12 to 13 month calving intervals. Olds (1979) found that

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[5] In this document, "heifer" refers to a milk-producing cow in her first lactation. Similarly, "mature cow" refers to a milk-producing cow in her second or greater lactation.

income over feed costs was reduced when calving intervals exceeded 12 months, by $1.18 per cow per day for mature cows and $0.71 per cow per day for first lactation heifers. Holmann et al. (1984) found that 13 month calving intervals would result in $0.21 to $0.40 per cow per day more income over feed costs than 15 month calving intervals in simulated Texas herds. Schmidt (1989) incorporated variable costs for bedding, marketing, and replacement, finding that calving intervals exceeding 13 months are associated with decreases in income over feed and variable costs of $0.10 to $0.71 per cow per day open. No changes were reported in the optimal calving interval at evaluated milk prices, feed costs, and milk yield levels (Holmann et al., 1984; Schmidt, 1989).

Van Arendonk and Dijkhuizen (1985) questioned the assumption that there exists an optimal calving interval for all cows. The results from their stochastic dynamic simulation model of insemination and replacement decisions indicated different optimal calving intervals for cows classes based upon parity[6], days open, and season of calving. Optimal calving intervals ranged from 12 to 18 months across these cow classes. Cow classes associated with greater persistency of milk yield in late lactation had longer optimal calving intervals, indicating that milk yield patterns through lactation were shown to influence the optimal calving interval. Limiting calving intervals for all cows in the herd to less than 16 months was associated with reduced net income.

[6] Lactation number, e.g., if parity equals one, the cow is in her first lactation.

2.1.2 Extended calving intervals with bST use

After the introduction of bST, a debate emerged about whether bST-related increases in persistency of milk yield lead to longer optimal calving intervals. Although results from field trials have suggested that bST use makes extended calving intervals profitable, methodological problems in theses studies lend question to whether this conclusion should be widely accepted.

Van Amburgh et al. (1997) conducted a field trial to evaluate extended calving intervals on “real farms.” Their conclusion that the delayed breeding group was more profitable than their short calving interval counterparts is questionable, due to significant methodological difficulties. The study randomly assigned cows in nine herds to 13.2 and 16.5 month calving interval groups, setting the minimum days to first service of 60 and 150 days, respectively. However, many cows in the trial did not become pregnant consistent with this planned schedule. As a result, milk yields at the end of lactation for these cows were projected using “standard adjustment factors” rather than actual data.

Arbel et al. (2001) conducted a similar study on high-producing Israeli herds with similar lactation curves to the Van Amburgh study. These investigators, too, concluded that the delayed breeding group was more profitable than the control group. In this study, however, the economic value of the groups was calculated on a per-day basis from the beginning of lactation through the first 150 days of the next lactation. Since the dry period is more diluted for cows with a longer initial lactation, values are biased toward longer calving intervals.

Jones (2000) evaluated these recommendations in a simulation using net present value (NPV) analysis to compare annualized returns across calving intervals with milk yield patterns consistent with bST use. Annualized returns were not improved with extended calving intervals; rather, returns were maximized with a 13 month calving interval. Jones concluded that extended calving intervals, up to 15 months, would be optimal only for lactations with unrealistically high persistency (<6% decline per month). These results were not sensitive to milk price, peak milk production, or opportunity costs of capital.

2.1.3 Herd reproductive decision analysis

The optimal calving interval question does not fully represent the reproductive management decisions made by a dairy farm manager. The managerial decision to change the current herd reproductive management system requires consideration of the benefits and costs of the decision. Improvements in reproductive performance may increase IOFVC but also require an investment in additional labor, training, or technology to improve estrus detection and / or breeding success.

The marginal change in net revenue associated with increasing reproductive performance, both EDR and CR, is highly related to previous reproductive performance (Pecsok et al., 1994). Reproductive performance improvements face diminishing marginal returns. Oltenacu et al. (1981) evaluated the profitability of improved reproductive efficiency with a dynamic simulation model that reflected the higher success rates and increased costs of more intensive reproductive efforts. The scenarios with highest profitability were at the middle values of reproductive performance (55% estrus detection rate and 50% conception rate). Diminishing returns on investment of time and money into breeding program were apparent above these levels.

Reproductive management decisions depend upon the methods and expected performance improvement associated with the change scenario under consideration. Hady et al. (1994) evaluated the decision to hire additional labor to improve reproductive performance on a Michigan dairy farm using a partial budget model. If the reproductive performance improved such that days to first service decreased from 80 to 60 days, EDR and CR increased from 50% to 60% and 35% to 50%, respectively, the total increase in net income was expected to exceed $18,000. However, if only CR was improved (to 40%), then the net income was expected to increase by $1,226. The net income change, as well as the decision to hire additional labor, were affected by milk price and replacement costs.

2.1.4 Herd analysis methods

A partial budget model, such as the one used by Hady et al. (1994), quantifies the total changes in the revenue and cost effects of the management change, holding all other aspects of the farm constant. The model isolates changes in net income that result from reproductive management changes. However, comparing the total change in net income across alternative management system changes requires that the alternatives have the same investment life. Also, opportunity cost of capital is not recognized using this method. Because the model is based upon changes in the average days open, it assumes that calving intervals within the heifer and mature cow groups are normally distributed.

Jones's (2000) net present value model views a cow's reproductive life as an investment – beginning with her purchase, continuing with cash flows through each lactation, and ending with a salvage value. The optimal calving interval is the one that maximizes annualized net income. This straightforward investment model accounts for opportunity costs and compares calving interval alternatives in standardized units. However, the model also requires a fixed number of lactations in a cow's productive lifetime, an unreasonable assumption on farms where culling is tied to reproductive performance.

The dynamic programming model developed by Van Arendonk and Dijkhuizen (1985) evaluates decisions to inseminate and (or) cull at each estrus throughout lactation, considering both the opportunity costs and the inherent risk and uncertainty in the decisions. The model was designed, however, to evaluate decisions within a reproductive management system, not potential changes to the system. Additionally, this complex model was not intended for on-farm use but rather for development of management guides for herd management decisions.

To evaluate reproductive management decisions, a herd needs a framework that:

- compares the values of reproductive performance under the current system with the proposed change by considering the marginal costs and benefits for the herd;
- incorporates opportunity costs of labor and capital in reproductive management changes;
- evaluates the calving interval alternatives in comparable units; and

- uses input information easily derived from common herd records.

2.2 Reproductive management as an investment

Reproductive management is an investment because it involves capital use that affects returns over time. A farm manager invests capital and other resources to accomplish pregnancy for cows in the breeding herd. The continuing investment into the reproductive system and the resulting reproductive performance influences returns to the dairy enterprise over the following years. Reproductive management and performance changes alter these herd returns in months and years after the change is implemented.

The herd reproductive investment can be subdivided into the investment in each cow-space in the herd. Each cow-space continuously contains a lactation; these lactations vary in calving interval. In a herd maintaining a constant size, each space in the herd is continuously occupied. Each lactation that is completed – by beginning a new lactation or exiting the herd – is "replaced' with another lactation. This replacement is equivalent to reinvestment in another lactation. The calving interval is thus the length of the investment in a lactation and, as such, its length defines the frequency of reinvestment. A lactation that included a pregnancy is replaced with a cow lactation, while a nonpregnant lactation ends with culling and is replaced with the lactation of a replacement heifer.

The dairy farm manager's decision to modify the current herd reproductive management system involves changes to both the lactation investments and the distributions of calving intervals (investments) across the herd. The additional investment in estrus detection and breeding involved in accomplishing a change in performance alters the cash flows of the individual lactations. Changes in herd reproductive performance alter the distribution of the calving intervals in the herd. An improvement in performance leads to a higher proportion of lactations with short calving intervals – with more frequent reinvestment. With consistent performance, the herd will ultimately reach a new steady state distribution that can be evaluated against the old one.

Decisions regarding reproductive management changes can be evaluated using investment analysis tools. Net present value examines changes in cash flow over time, reflecting the inherent lag between investment and return associated with the capital investment. To evaluate a potential reproductive management change, we quantify the changes to the value of the calving interval distribution – both the changes in the lactation investments and the change in the frequency of reinvestment. We can then compare the total herd value across all considered reproductive management scenarios and selecting the scenario with the highest value.

2.3 Conceptual model

A present value simulation model was developed to evaluate potential changes to a reproductive management system. The conceptual model, depicted in Figure 2.1, is adapted from Jones's (2000) calving interval analysis for use with herd reproductive management decisions. The model is not intended to determine the optimal calving interval, but rather it allows comparison of the values of alternative reproductive management changes. This model evaluates only the difference between the value of the "original" herd and the same herd after the management change once steady state has been reached. The adjustment time required for implementation is not accounted for in this analysis.

The goal of the analysis is to determine the expected change in herd value if the proposed reproductive management change were adopted. A proposed change should only be adopted if the expected value of the herd with the proposed change exceeds the herd's value under the current reproductive management system. These values can be determined by evaluating the reproductive management investments in each lactation and the calving interval distributions under the current and proposed reproductive management systems.

Determining the values of the current and proposed reproductive management systems is a four-step process. First, the cash flows in lactations of different calving interval scenarios are quantified and standardized to their value at the beginning of lactation using present value analysis. Then, annuity equivalent values of each of these lactations can be determined and the annualized values compared. The herd value is the weighted sum of the annuity equivalent values according to the distribution of calving intervals. Finally, the values of alternative management change scenarios can be compared.

2.3.1 Step one: Determining the present value of lactation

The first step is to determine the value of each calving interval's lactation standardized to the same point in time – the beginning of the lactation, at calving – for each management change scenario. The present value of lactation is calculated by using the farm's opportunity cost of capital to discount the cash flows in each period of lactation to the first period. The farm's opportunity cost of capital is the return that one could earn from the best alternative use of capital. The sum of the discounted cash flows represents the present value of the lactation:

$$(1) \quad PV_{ij} = \sum_{n=1}^{N} [CF_{nj} * PVIF_{k,n}], \text{ and}$$

$$(2) \quad PVIF_{k,n} = \frac{1}{(1+k)^n},$$

where PV_{ij} = present value of lactation with calving interval *j* in scenario *i*,

CF_{nj} = incremental after tax cash flow for calving interval *j* in period *n*,

N = total number of periods, and

$PVIF_{k,n}$ = present value interest factor with discount rate *k* for period *n*,

k = farm's opportunity cost of capital (discount rate).

All cash flow changes affected by calving interval are included in the present value calculation. This includes cash flows that vary in magnitude and (or) timing across calving intervals (e.g., milk income, feed costs). Those cash flows associated with specific stages of lactation (e.g., fresh cow, breeding, and dry cow costs) must also be incorporated, since the effects of reinvestment frequency changes will be reflected in the annuity calculation. These cash flow changes may be comprised of the changes in revenues and expenses after taxes, the depreciation tax shield, and net working capital.

2.3.2 Step two: Calculating the annuity equivalent

Because the present values of each lactation represent investments of different lengths they must be converted to a repeating annualized value for any comparison to take place. The calving intervals can be compared on the basis of annualized expected return by converting the present value of the lactation to their annuity equivalent value. The annuity equivalent is the perpetual stream of income that a lactation with the particular calving interval would generate each year given an infinite constant scale replacement of the calving interval at the opportunity cost of capital. Constant scale replacement implies that, within the herd, each lactation with a 15 month calving interval is replaced with another lactation with the same calving interval and an identical cash flow stream (i.e., milk revenues). The replacement lactation is not necessarily from the same cow.

The annuity equivalent value for each calving interval for each lactation is the present value of the lactation adjusted by an annuity factor based upon the investment's length,

$$(3) \qquad AE_{ij} = \frac{PV_{ij}}{PVIFA_{k,n}} ,$$

$$(4) \qquad PVIFA_{k,n} = \frac{1 - \dfrac{1}{(1+k)^n}}{k} ,$$

where AE_j = annual equivalent value of calving interval *j* in scenario *i*, and

PV_{ij} = present value of lactation for calving interval *j* in scenario *i*,

$PVIFA_j$ = present value annuity factor for calving interval *j*,

k = monthly discount factor, and

n = total number of periods (months) in the calving interval.

2.3.3 Step three: Incorporating the change in the herd structure

The annualized values for the current and the proposed management scenario account for the change in the value of each of the calving interval investments. The distribution of these calving intervals in the herd will also change. With a consistent pregnancy rate culling rates for both reproductive and nonreproductive culls, the herd will eventually settle into a steady state calving interval distribution. That is, the number of lactations in the herd with each calving interval will be stable over time. Once this steady state distribution is determined, the value of a scenario can be calculated as the weighted sum of the annualized values of the calving intervals by the scenario's steady state distribution:

$$(5) \quad V_i = \sum_{j=1}^{J} [AE_j * p(CI_j)],$$

where V_i = value of scenario *i* to the herd,

$p(CI_j)$ = number of cows in the herd with calving interval *j* under scenario *i*.

2.3.4 Step four: Comparing alternative management scenarios

If the scenario value of the proposed change exceeds the current scenario value, then the investment adds value to the herd and should be undertaken. If not, then the current reproductive management system should be maintained. A scenario with a lower value than the current herd is expected to decrease the value of the herd and should not be implemented. If multiple changes are under consideration, then the value of each scenario should be compared to the current herd value. If the changes are mutually exclusive, then the highest positive value change should be implemented.

2.4 Reproductive management groups

The identical constant scale replacement assumption implies uniformity in reproductive management decisions, pregnancy rates resulting the same management system, and all analytical components (e.g., milk yield patterns over the course of lactation) across all cows in the analysis. While this may not be valid for an entire herd, many herds are subdivided into groups of cows with similar characteristics in order to improve management efficiency. Cows are treated uniformly within these management groups, managed for the best interests of the group rather than an individual cow.

2.4.1 Parity and season of calving as management groups

Season of calving and parity are common bases for management groups in many herds. First lactation heifers have different physiological needs than mature cows, since they have not reached full maturity at the time of calving. In some herds, cows are physically separated into these parity groups to better meet the nutritional and social needs of first lactation heifers. Season of calving groups are separated by time, and differences in management across season vary across farm.

Milk yield patterns

Both parity and season groups influence milk yield patterns over the course of lactation.. Factors such as nutrition, health, and climate may influence peak yield and (or) the rate of milk yield decline itself, depending upon the stage of lactation and nature of the effect. Heifer milk yields peak lower, at a later lactation stage (days in milk), and decline at a slower rate (pounds of milk yield loss per day) (Friggens et al., 1999). Heifers are also less subject to the accelerated milk yield decline in late stages of pregnancy – that is, they show a smaller pregnancy effect (Oltenacu et al., 1980). Also, total milk yields of heifers are consistently lower than that of their mature counterparts.

Season of calving impacts the shape and scale of the lactation curve, with particular effects on persistency (Danell, 1982a). Seasonal patterns tend to occur similarly each year within a particular herd, although the nature of these patterns are unique to each herd (Rowlands et al., 1982). The season of calving effect in most herds consists of seasonal heat stress and feed changes, which are common in the spring and summer (Garcia and Holmes, 2001). These seasonal milk yield effects interact significantly with stage of lactation (Ngwerume, 1994).

As a result, the lactation curves of cows calving in various seasons reflect these effects differently. Garcia and Holmes (2001) found that spring calving cows in New Zealand show more persistent milk yields than their winter calving counterparts. Cows calving in summer show consistently lower but more persistent production than their fall and winter calving herdmates (Ngwerume, 1994). Oltenacu (1980) found that cows calving July through September showed the largest pregnancy effect.

2.4.2 Management groups in reproductive analysis

Because of differences in management and milk yield patterns, parity and season of calving are key determinants of the value of reproductive performance improvement. In particular, first lactation heifers are expected to have smaller production and profit losses than mature cows due to their more persistent milk yields (Olds et al., 1979). Modeling seasonal differences in milk production, both James and Esslemont (1979) and Delorenzo et al. (1992) found notable differences in the optimal calving interval across cows calving in different seasons. These differences are evident across annuity equivalent values calculated for each management group.

Reproductive decisions for management groups cannot be accurately analyzed separately because management groups are not independently affected by herd reproductive management changes. When pregnancy rates and the resulting calving interval distributions are different across groups of cows, the relative sizes of management groups may change. For example, if pregnancy rate of cows calving in the summer decreases (or improves less than) winter calving cows, winter calving cows will comprise a greater proportion of the herd at steady state. When relative management group sizes shift due to reproductive performance changes, the tradeoff of one group for another creates an opportunity cost.

In addition, the relative sizes of management groups are heavily influenced by culling assumptions in the reproductive analysis. If culling is assumed to occur consistently after a constant number of lactations or months in the herd, then relative management group sizes do not change. In most herds, however, a fixed number of cows are culled each year for reasons not related to reproductive performance, such as low production, injury, or illness. In addition, cows are culled if they fail to conceive by a particular stage of lactation, i.e., the calving interval becomes too long. Under these culling guidelines, unequal reproductive performance across groups leads to unequal culling (and replacement), which results in unequal management group sizes. For example, a disproportionate improvement in heifer reproductive performance would lead to relative increases in the culling of mature cows, resulting in a greater proportion of first lactation heifers comprising the herd.

Analysis of herd reproductive management changes can incorporate the differences in annuity equivalent values across management groups. The annuity equivalents and calving interval distributions are weighted by management group sizes in Step three to account for the relative change. Steady state management group sizes are determined using the pregnancy rates and culling rates for each management groups to quantify the movement between each group. Figure 2.2 depicts the defined paths of cows in the herd across four management groups -- parity (heifer and cow) and two seasons. In steady state, group sizes are stable -- no net movement occurs between groups, and movement in equals movement out of each group. Movement between groups is quantified and used to determine the number of cows in each steady state management group.

2.5 Empirical model

The simulation model was developed to quantify the value of alternative reproductive management scenarios related to changes to the estrus detection system. Such changes could include allocating additional labor to visual observation or replacing visual observation with a number of technology alternatives in order to increase the estrus detection success rate. Because of the number of management alternatives available, estrus detection usually offers more potential to improve reproductive performance than other aspects of reproductive management (Stevenson, 2001).

Cows were pooled into eight management groups, defined by parity and season of calving. Two parity groups were defined as heifers (first lactation) and cows (second and later lactations). Four season of calving management groups were defined, each representing three calendar months of the year. A uniform distribution of calving over the months within each season of calving management groups was assumed.

As shown in Table 2.1, ten calving intervals were examined at three week intervals (the length of one estrus cycle) from 11.5 months to 17.75 months. The lengths of pregnancy (gestation) and the dry period were fixed at 40 weeks (280 days) and 8 weeks (56 days), respectively. Lactations that would remain nonpregant beyond 264 days in milk, consistent with the 17.75 month calving interval, are considered cull lactations. This criterion is consistent with the longest optimal calving intervals found in Van Arendonk and Dijkhuizen (1985).

An additional lactation was developed to represent lactations that terminate with culling for reproductive reasons. Reproductive cull lactations continue for 12 months, at which time the lactation is simultaneously terminated via culling and replaced with a new heifer lactation. In this model, culling occurs at 365 days in milk (or earlier if milk yield falls below 50 pounds per day). Replacement occurs at the end of the 365 day lactation, regardless of the "date" of culling. Thus, all cull cow and heifer lactations are replaced with a heifer lactation in the same season of calving.

The conceptual model outlined in Section 2.3 can be applied more generally than the model proposed here. The model can be modified to accommodate any change in herd reproductive performance, such as new breeding techniques or a change in the time of first breeding. The model could be also modified for use with other management groups, calving intervals, and culling assumptions. This discussion is beyond the scope of this research.

2.5.1 Step one: Determining the present value of the lactation

Establishing cash flow vectors

The columns of each matrix represent the calving intervals in the management group, with the net cash flow in each period (3 weeks) through the lactation represented in each row. Because the longest calving interval has 26 periods, all cash flow matrices have 26 rows. The matrices of expected net cash flows for calving intervals in each management group are created from individual cash inflow and outflow matrices of elements affected by a change in reproductive management. The net cash flow matrix is calculated by combining the cash inflow and outflow matrices:

$$(6) \quad \mathbf{CF}_{jmn} = \sum_{p=1}^{P} \mathbf{IN}_{jmn} - \sum_{q=1}^{Q} \mathbf{OUT}_{lmn}$$

where $\mathbf{CF}_{jmn}$ = a j x n matrix representing the net cash flows in each period n for a lactation with calving interval j in management group m,

$\mathbf{IN}_{jmn}$ = a j x n matrix representing cash inflows in each period n associated with cash inflow activity p and calving interval j in management group m,and

$\mathbf{OUT}_{lmn}$ = a j x n vector representing cash outflows in each period n associated with cash outflow activity q and calving interval j in management group m.

All changes in after-tax revenues and expenses, depreciation, and net working capital that vary in magnitude or timing across calving intervals, in addition to those associated with specific stages of lactation must be included in the analysis. Relevant cash inflows include milk, calf, and culling revenues. Relevant cash outflows consist of feed, veterinary, breeding, labor, dry cow, and replacement expenses. Matrices were developed based upon cash flows grouped for similar production structures. The elements of each matrix (e.g., milk, feed) were derived from a matrix of the expected physical units of each cash flow event in each period over the lactation multiplied by a scalar unit price.

Labor and tax expenses. Because of their intricate relationship with specific events and cash flows throughout lactation, changes in labor and tax expenses are incorporated into the cash flow matrix for the activity in which it is used. The tax structure in this analysis reflects a sole proprietorship or partnership farm operation. All revenues and expenses in this analysis are considered taxable at the ordinary income tax rate, except as noted.

Labor costs associated with the change in calving interval consist of the wages paid for hired labor and the opportunity cost of management labor. Hired labor costs are considered variable to the dairy enterprise at an hourly rate consisting of all wages and benefits provided. Management labor on a dairy farm is often a scarce resource; as such, allocating it to reproduction requires that it be removed from another farm activity. Thus, management labor use for reproductive management represents an opportunity cost to the remainder of the farm operation. Since such opportunity costs represent lost income, they are considered tax deductible at the ordinary income tax rate.

Milk revenues and feed expenses. Milk revenues are affected by both the change in lactation length and frequency with which a new lactation begins. Shorter calving intervals are inherently associated with a shorter lactation, but the high yield stages early in lactation occur more frequency. Milk revenues are calculated for each period of lactation (excluding the dry period) using an empirical lactation curve fitted to herd milk yields. Alternative lactation curve specifications and the applicable empirical methods will be examined in Chapters 3 and 4.

Feed expenses are closely associated with milk production, as additional feed intake is required to support the additional milk production. One additional pound of feed on a dry matter basis is required for every 2.0 pounds increase in milk production (Council, 1988). Feed expenses are deducted at the ordinary income tax rate (1999). The formulation of the ration would remain constant, since the milk production change results from truncated lactation length and more frequent calving. Feed expenses are directly associated with milk production and assessed in the same period.

Fresh cow revenues and expenses. Calf revenues, veterinary expenses, and herd health labor costs that occur in the first month of lactation are realized more frequently with shorter calving intervals. All calves are considered to be sold by the dairy herd enterprise. Bull calves are typically sold in the weeks following birth, and heifer calves are sold or transferred to the replacement heifer enterprise. Mastitis and metabolic disorders are most prevalent in the first few weeks of lactation. Cows afflicted with these disorders require veterinary care and additional labor for their treatment. Cows and calves require special care during the first weeks of lactation, requiring allocation of additional labor.

Breeding expenses. Breeding expenses vary with calving interval when the estrus detection rate is changed. A voluntary waiting period of 60 days was used for this analysis. All cows were considered eligible for estrus detection, and if detected, breeding. Anestrus and other factors delaying days to first service were not modeled. All cows detected in estrus are serviced. The breeding and associated labor costs for one breeding are associated with the last breeding for each calving interval. An expected number of breedings equal to the estrus detection rate would apply to all prior periods after 60 days in milk. Breeding and associated labor expenses are taxable at the ordinary income tax rate.

Culling and replacement. Only cull cow sales associated with reproduction are considered in this analysis, as other culling strategies are assumed unaffected by reproductive performance. Culling revenues and replacement costs are assessed in the last period of a cull lactation. Replacement expenses consist of the expenses associated with obtaining the replacement animal. Income from the sale of cull cows is taxed at the capital gains tax rate. To facilitate analysis, heifer calves are considered sold and replacements purchased. Replacement purchases result in a non-deductible change in cash flow that alter the farm's depreciation over the 5-year MACRS investment life. The purchase of replacement heifers increases the farm's depreciation tax shield.

Variable dry period expenses. Unlike feed for the milking herd, feed expenses for dry cows are not tied to milk production. Rather, dry cow feed expenses are assessed on a daily basis. A constant dry period of eight weeks was considered for all lactations. Dry cow costs were realized in the last three periods of the lactation. Although the amount of dry period expense does not vary across calving intervals, the calving interval does determine the frequency with which this expense is realized. Shorter calving intervals are associated with a greater proportion of time spent in the dry period.

Present value of lactation

The net cash flows by period can be discounted back to determine the present value of each lactation in management group *m*. The present value represents the value of the lactation at the beginning of that lactation. The values across calving interval represent different lengths of time. The present value of the lactation is determined from the product of a present value interest factor matrix and the net cash flow matrix for each management group:

$$(7) \quad \mathbf{P}_m = \mathbf{PVIF}_{k,n} * \mathbf{CF}_{jm},$$

where $\mathbf{P}_m$ is a 1 x *j* column vector containing the present values of lactation for calving interval *j* in management group *m*,

$\mathbf{PVIF}_{k,n}$ is a *n* x 1 row vector containing the present value interest factor for each period *n* (since calving) in a lactation, based upon the herd's discount rate k, and

$\mathbf{CF}_{mn}$ is the net cash flow matrix representing the cash flow in each period *n* for lactations with calving interval *j* in management group *m*.

2.5.2 Step two: Calculating annuity equivalents

The column vectors $\mathbf{P}_m$ that contain the present value of lactation for calving intervals within each management group can be combined into a single 11 x 8 matrix for the herd, with each element [m,j] representing the present value for a lactation in management group *m* with calving interval *j*. The $\mathbf{A}$ matrix, which contains the annuity equivalent values for calving intervals in each management group, is derived by multiplying the $\mathbf{P}$

matrix by a square matrix, the diagonal elements of which contain annuity factors with the respective k and n values. That is,

(8) $\mathbf{A}_{jm} = \mathbf{P}_{jm} * \mathbf{PVIFA}_{k,n}$

where $\mathbf{A}_{jm}$ is a j x m matrix containing the annuity equivalent values for lactations in each management group m with calving interval j,

$\mathbf{P}_{jm}$ is the m x j matrix containing the present value of lactation by calving interval and management group, and

$\mathbf{PVIFA}_{k,n}$ is a square j x j matrix containing the present value interest factor for annuities with reinvestment in the nth period, based upon the herd's discount rate k.

2.5.3 Step three: Incorporating changes in herd structure

Determining calving interval distributions for each management group

The $\mathbf{A}$ matrix contains annualized values for each of the calving intervals in each management group. In determining the total herd value, expected calving interval distribution must be calculated for each management group. These calving interval distributions can be calculated from the pregnancy rates for each management group, since the pregnancy rate indicates the expected proportion of nonpregnant cows conceiving in each estrus period. Let $\mathbf{C}$ be a m x j matrix such that

(9) $\mathbf{C}[m,j] = PR_m * NP_{m,j-i},$

where $C[m, j]$ is element [m,j] in matrix **C**, the proportion of the management group m with calving interval *j*,

PR_m = the pregnancy rate for management group *m*, and

$NP_{m,j-1}$ = the proportion of the management group not pregnant after estrous cycle associated with calving interval *j*.

Calculating management group sizes

The steady state distribution of cows across management groups can be derived from a transition matrix **T** and a herd size matrix **M**. Each element m_1, m_2 in **T** represents movement from group m_1 to group m_2 and can be derived from equations defining each management group by the composition of that movement. One row must be modified to reflect the total herd size as the sum of the groups. The result is

$$(10) \quad \mathbf{TX} = \mathbf{H},$$

where **T** is a square *m* x *m* matrix, representing the steady state movement amongst management groups *m*,

X is a 1 x *m* row vector of variables identifying the number of cows in each management group where the cows originated, and

H is an *m* x 1 matrix identifying the net result of the movement amongst management groups. All elements are zero except in the row modified to represent the sum of the groups totaling the herd size, where the element contains the size of the milking herd.

Rearranging equation (9), the steady state management group sizes – contained in the **X** matrix – can be solved as

$$(11)\quad \mathbf{X} = \mathbf{HT}^{-1},$$

where $\mathbf{T}^{-1}$ = inverse of matrix **T**.

Determining herd structure

The **S** matrix represents the steady state distribution of the herd by management group and calving interval. Combining the management group sizes -- the diagonal elements of matrix **X** -- with the with calving interval distribution for each management group – matrix **C** -- the number of cows with each calving interval in each management group can be calculated as

$$(12)\quad \mathbf{S} = \mathbf{C} * \mathrm{diag}(\mathbf{X}),$$

where **S** is a j x m matrix identifying the number of cows with calving interval j in each management group m,

C is a j x m matrix of the calving interval distribution for each management group, where each element [j,m] is the proportion of each management group m having the calving interval j, and

diag(**X**) is a m x 1 vector containing the diagonal values from matrix **X**, the groups sizes of each management group m.

Total herd values for each reproductive management scenario

The value of reproductive management alternative *i*, $\mathbf{V}_i$, is the sum of the diagonal elements of a matrix created from the product of the new herd distribution and the annuity equivalent value matrices:

$$(13)\quad \mathbf{V}_i = \Sigma\ \mathrm{diag}[\mathbf{AS}]_i - \mathbf{I}_i,$$

where $\Sigma\ \mathrm{diag}[\mathbf{AS}]_i$ is the sum of the elements in a *m* x 1 vector of the diagonal elements from the product $\mathbf{AS}_i$,

$\mathbf{A}$ is the *m* x *j* matrix containing the annuity equivalent values for calving intervals in each management group -- element $[m, j]$ is the annuity equivalent value for a lactation in management group *m* with calving interval *j*,

$\mathbf{S}$ is a *j* x *m* matrix identifying the number of cows with calving interval j in each management group, and

$\mathbf{I}_i$ is a scalar value of the annuity equivalent value of any residual implementation costs for scenario *i*.

2.5.4 Step four: Comparing alternative scenarios

The value of each alternative management change scenario, $\mathbf{V}_i$ is compared to the value of the current management system, $\mathbf{V}_0$, to determine if the management change is undertaken. If $\mathbf{V}_i > \mathbf{V}_0$, then the investment is expected to add value to the herd and should be implemented. If not, then the current reproductive management system should be maintained, since implementation is expected to decrease the value of the herd and should not be implemented. For multiple projects, each $\mathbf{V}_i$ should be compared, and the highest value scenario selected.

2.6 Summary and Conclusions

A reproductive management decision analysis model was developed to evaluate expected changes in herd value associated with specific alternative management change scenarios. Changes in the management system and reproductive performance were evaluated by calculating present value and annuity equivalent values for lactations with different calving intervals. To determine the total herd value under the proposed management system, the annualized values were associated with the calving interval distribution based on the expected reproductive performance of the proposed system. Change scenarios can be evaluated by comparison to the value of the current management system and amongst alternatives. This model examines only the current management scenario against alternative management change scenarios once they reach steady state. The model does not account for herd values while the herd is in transition.

This model utilizes herd information that can be derived from common herd management and financial records. Most input information can be calculated from herd prices, statistics, and characteristics. Like other model inputs, information for milk yield projections is available in the production records of most records. Herd managers wishing to fit an empirical lactation curve model to their herd's data to assist in milk yield projections have a number of options. However, the tradeoff between effort and accuracy is not clear from past research.

The remainder of this thesis evaluates the use of empirical lactation curves for milk yield projection for reproductive management decision analysis. In Chapter 3, milk yield data for a herd is analyzed using commonly recommended empirical lactation curves from the literature. The milk yield projections resulting from these lactation curve models are used in a reproductive analysis for the herd in Chapter four to determine if the choice of lactation curve model influences reproductive analysis results.

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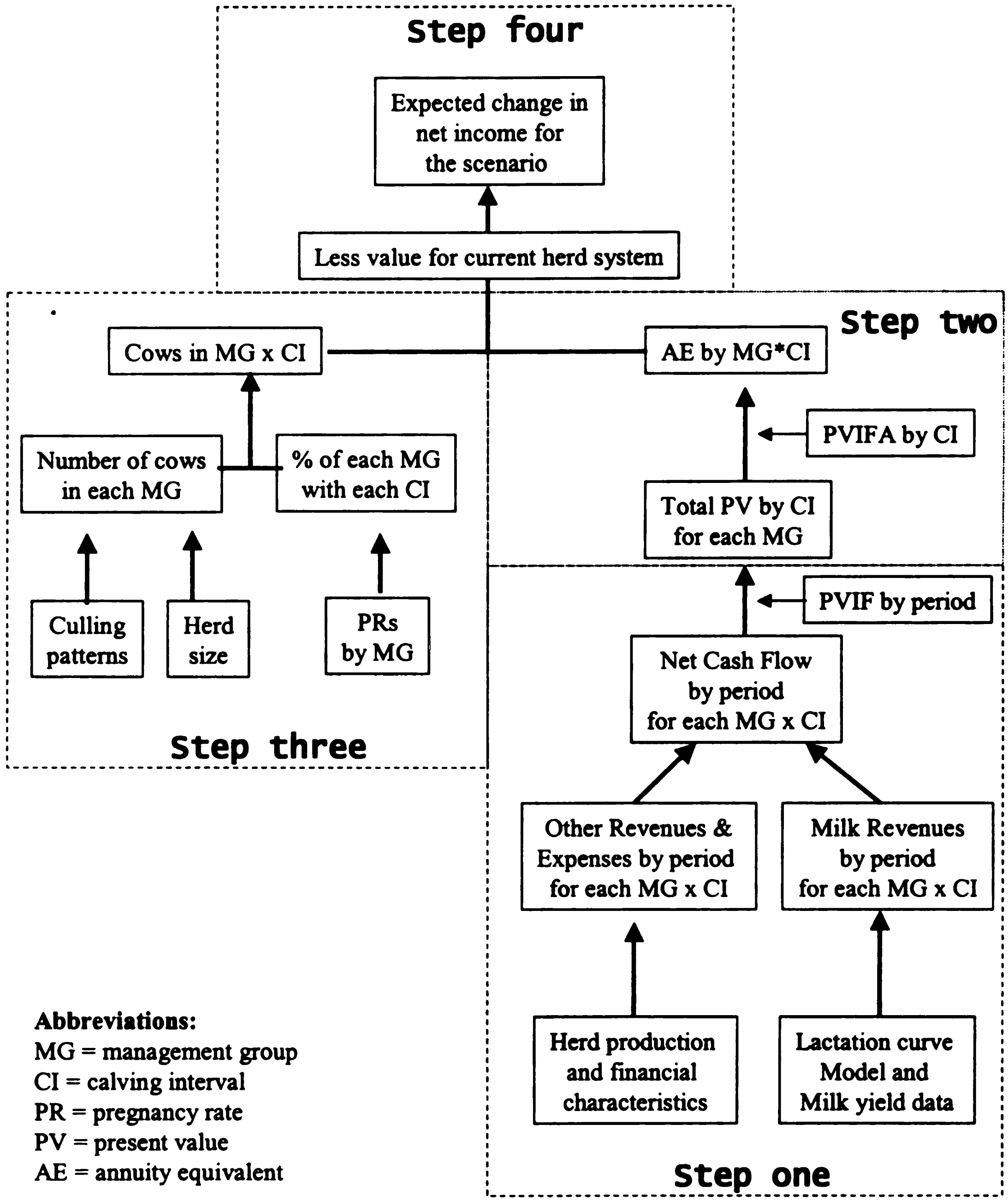
Table 2.1 Calving intervals examined in the empirical analysis.

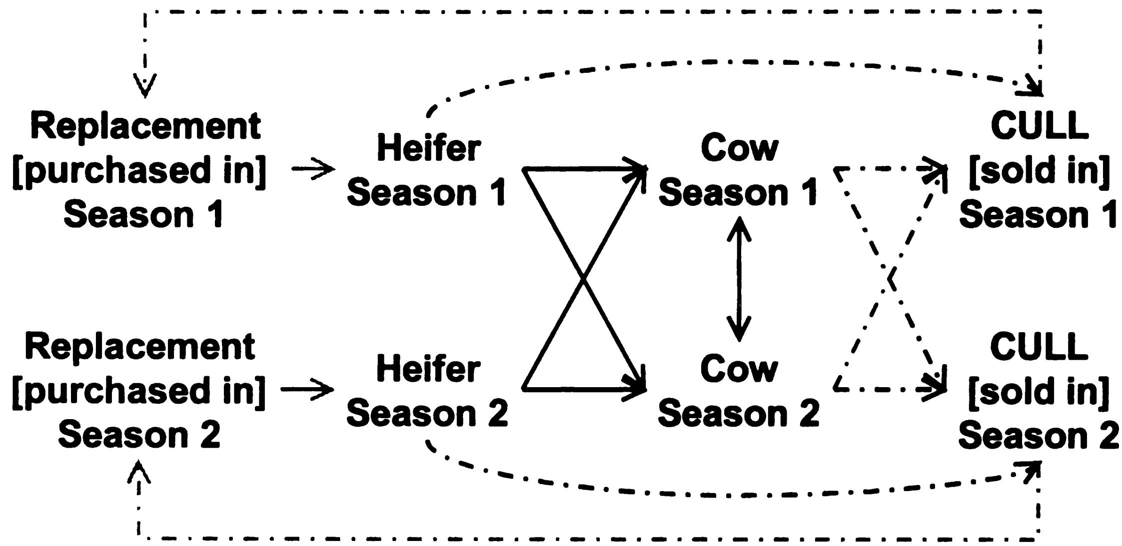
Calving interval		Lactation length		Lacating and Open		Lactating and Pregnant	
wks	mos	wks	days	wks	days	wks	days
50	11.54	42	294	10	70	32	224
53	12.23	45	315	13	91	32	224
56	12.92	48	336	16	112	32	224
59	13.62	51	357	19	133	32	224
62	14.31	54	378	22	154	32	224
65	15.00	57	399	25	175	32	224
68	15.69	60	420	28	196	32	224
71	16.38	63	441	31	217	32	224
74	17.08	66	462	34	238	32	224
77	17.77	69	483	37	259	32	224

Figure 2.1. Evaluation model for changes to a herd reproductive management system.



Abbreviations:
MG = management group
CI = calving interval
PR = pregnancy rate
PV = present value
AE = annuity equivalent

Figure 2.2. Cows move through management groups in the herd in defined patterns.



First lactation heifers and mature cows enter a cow lactation at calving. (Season depends on calving interval.)

Heifers and cows culled at the end of lactation.

Replacement heifers enter the herd at calving, in the same season as the cull.

Cull cows and heifers are replaced with a replacement heifer, purchased in the same season as the cull.

Chapter 3

USING LACTATION CURVE MODELS TO EXTEND LACTATION IN HERD REPRODUCTIVE ANALYSIS

Reproductive decision analysis for a farm hinges upon an accurate projection of the expected change in milk yield associated with the reproductive performance change. Reproductive performance influences milk yield by changing the length of calving intervals of cows in the herd. The opportunity cost of extending the calving interval is the early lactation milk yield that the additional segment of milk yield replaces. Similarly, this late lactation milk yield is the opportunity cost of reducing the calving interval – this segment is replaced with early lactation milk yield when lactation is shortened.

An accurate projection of the change in milk yield associated with a change in calving interval requires capturing the rate and shape of the milk yield decline. This change is based upon an extension or truncation of the mathematical model used to characterize the lactation curve. Reproductive simulation models often project changes in milk yield with standard adjustment factors based upon large sets of regional data with variables that systematically influence milk yields, such as climate or parity. While these projections are representative of a uniform set of herds with similar characteristics to the data set, they do not provide appropriate guidance for the individual farm looking to conduct their reproductive management decision analysis with their own lactation curve data.

Lactation curves for an individual herd can be more accurately characterized using individual herd milk yield data, particularly with daily milk weights. However, accurately calculating the expected change in herd milk yield from their data requires a functional form for the lactation curve model that adequately characterizes the lactation curve shape (persistency) of the herd and its management groups. Most simulation reproductive analyses are based upon the Wood model due to its simplicity (Hady et al., 1994; Jones, 2000; Wolf, 1999). However, other studies indicate systematic problems with the Wood model's fit, and nonlinear models have been proposed.

In this chapter, the first objective is to determine if there is sufficient variation in lactation curve shape within a herd to question the accuracy of the Wood model for reproductive analysis. This is accomplished by examining the variation in lactation curve shapes of cows in a herd. A lactation curve model was developed to measure the decline rate and possible changes in that rate and fitted to individual lactations. Results indicate that indeed decline rate and the change in the decline rate does vary across cows, potentially by management group. Common lactation curve models were then fit to pooled daily milk yield data for each management group and the differences in the characterizations of lactation curve shape examined. The results from these lactation curve models are incorporated into a reproductive management decision model in Chapter 4 to determine the degree to which choice of lactation curve model influences analytical results.

3.1 Lactation curve models for herd reproductive analysis

For reproductive analysis, we are projecting the milk yield change associated with changing the length of lactation and the onset of pregnancy. Lactation typically ends two months prior to the next calving to allow sufficient physical preparation for the next lactation. A shorter calving interval has an earlier onset of pregnancy and, thus, fewer days in lactation. In contrast, a longer calving interval has more days before pregnancy begins and so lactation continues longer.

Ascent and peak yields are not affected by the calving interval. Delaying pregnancy alters the stage of lactation (days in milk) in which the milk yield depression associated with late gestation begins This "pregnancy effect" begins earlier in lactation with shorter calving intervals than for longer calving intervals. The total effect of changing lactation length is the accumulated change in milk yield over the course of a lactation resulting from the delayed pregnancy effect. Thus, the portion of the lactation curve that is extended when pregnancy is delayed is the milk yield decline pattern *before* the pregnancy effect begins, as demonstrated in Figure 3.1.

Empirical lactation curve models are commonly used to project lactation milk yields for hypothetical differences in the calving interval. The prediction for the change in milk yield at the end of lactation is affected by the way the model depicts peak yield, persistency, and the pregnancy effect. Parametric lactation curve models provide structure to extension that allows prediction outside of the data set. Accurate projection of the milk yield change requires that the model accurately characterize the trend in milk yield decline as well as the onset and magnitude of the pregnancy effect. This allows accurate prediction of the change in milk yield due to lactation extension or truncation and shifting of the pregnancy effect when simulating changes in the calving interval length.

3.1.1 Lactation curve functional forms

Many functional forms for the lactation curve have been proposed in the dairy science literature. Most involve a tradeoff between the quality and consistency of fit, based partially upon the flexibility of the lactation curve shape, and the complexity of the mathematical form and statistical methods required to fit the curve. Table 3.1 shows the results of a evaluation study from Vargas et al. (2000), comparing the quality of fit of these models.

1. Wood model

The lactation curve model proposed by Wood (1967) is the functional form most commonly used in analyses that require fitting milk yield data. The Wood model, or parts of it, have been used in reproductive analyses (Hady et al., 1994; Jones, 2000; Wolf, 1999), as well as other applications that involve fitting data (Freeze and Richards, 1992; Schaeffer and Jamrozik, 1996). Its popularity is due in large part to its simple mathematical form:

(14) $Y_t = a\ t^b\ e^{-ct}$,

where Y_t = milk yield on day t of lactation, and

t = days in milk on lactation day t.

The equation usually estimated using linear regression techniques is its logarithmic form,

$$(15)\quad \ln Y_t = \ln a + b \ln t - ct.$$

Despite its convenience, extensive evaluation of the Wood model indicates systematic lack of fit, causing autocorrelated residuals and biased predictions of completed lactations (Congleton and Everett, 1980; Olori et al., 1999; Vargas et al., 2000). In particular, the Wood model is inadequate in describing the time and yield of peak, leaving high positive residuals in early lactation (weeks 5 to 10) and negative residuals in mid lactation (weeks 10 to 25) (Olori et al., 1999). Its depiction of milk yield decline as proportional rate of change overestimates late lactation milk yields (Vargas et al., 2000).

2. Morant model

Morant and Gnanasakthy (1989) expanded upon Wood's incomplete gamma model to provide a more flexible form for persistency,

$$(16)\quad \ln y_t = a - b_1 t'^2/2 + b_2/t + c(1+t'/2)t'),$$

where $t' = (t - 21.4)/100$.

Unlike the Wood model, the relative rate of change in this model does not necessarily fall to constant value in mid and late lactation. Rather, the second derivative is a horizontal asymptote. As a result, this model fits extended lactations far better than the Wood model, showing higher R^2 values and less autocorrelation among residuals. Indeed, the Morant model fit was the only linear model recommended for use in fitting lactation milk yields across evaluation studies (Morant and Gnanasakthy, 1989; Perochon et al., 1996; Vargas et al., 2000)

3. Diphasic model

The diphasic model takes the form:

$$(17)\quad Y_t = a_1 b_1 \tanh^2 [b_1(t^{\gamma} - c_1)] + a_2 b_2 \tanh^2 [b_2(t - c_2)],$$

where a_1 = ½ asymptotic total yield in phase 1,

b_1 = rate of yield relative to a_1 per day in phase 1,

c_1 = day of peak yield in phase 1,

γ = power transformation of time,

a_2 = ½ asymptotic total yield in phase 2,

b_2 = rate of yield relative to a_2 per day in phase 2, and

c_2 = day of peak yield in phase 2.

Vargas et al. (2000) describes the diphasic model, proposed by Grossman and Koops (1986), as the best fitting empirical mathematical model for both standard and extended lactations. As a result of the fit, this model has been increasingly used in lactation curve applications, although it has not yet been included in a reproductive analysis. The primary limitations of the diphasic model include unintuitive parameters and large data requirements (i.e., degree of freedom problems do not allow estimation from monthly milk data), as well as a common failure to satisfy convergence criteria when analyzing daily milk yield data from individual cows.

4. Lactation persistency model

The lactation persistency model (LPM), a linear spline model with two knots, represents milk yield through lactation as three connected linear segments -- a linear ascent, a flat peak, and a linear descent, smoothed with exponential terms. The empirical form, proposed by Grossman et al (1999), is:

$$(18)\quad y_t = y_P + b_1(t-t_1) - r_1 b_1 \ln\frac{[e^{t/r1}+e^{t1/r1}]}{[1 + e^{t1/r1}]} + r_2 b_3 \ln\frac{[e^{t/r2}+e^{(t1+P)/r2}]}{[1 + e^{(t1+p)/r2}]},$$

where t_1 = days in milk at start of constant peak yield,

y_P = constant peak yield,

P = duration of constant yield,

b_1 = slope of yield ascent,

b_3 = slope of yield descent,

r_1 = duration of transition 1 (ascent → peak), and

r_2 = duration of transition 2 (peak → decline).

Vargas (2000) found the LPM model nearly comparable in fit to the diphasic model, but like the diphasic model, it frequently failed to converge with daily milk yield data. Its primary advantage is the intuitiveness of its parameters – each parameter measures a distinct aspect of lactation curve shape.

3.1.2 Persistency: Modeling milk yield decline

Persistency is generally defined as the degree to which milk yield is maintained at peak level – the milk yield pattern in the declining phase of lactation (i.e., after peak). Important properties of persistency are the rate of change in milk yield in the decline phase of lactation and the change in the rate of decline. Empirically, persistency can be defined as the lactation equation's first derivative of milk yield, and the change in persistency, as the second derivative in the decline phase of lactation – after peak yield.

These four lactation curve models depict milk yield decline (persistency) very differently, as depicted in Figure 3.2. The Wood model shows milk yield decline that converges to a constant proportional rate of change. The LPM model, in contrast, depicts a linear decline. The Morant model allows a more flexible shape for decline, as does the Diphasic model with multiple decline phases.

A significant literature is available regarding most appropriate functional form. Despite the abundance of persistency measures in the literature, little light has been shed upon the true shape of milk yield decline. Although lactation curve model comparisons typically indicate that functional forms allowing variation in milk yield decline shape show the best fit, the cited reason is often *early* lactation fit (Olori et al., 1999; Vargas et al., 2000). The Wood model, in particular, has been shown to have poor fit in late lactation and has thus been deemed not suitable for modeling extended lactations (Rowlands et al., 1982; Vargas et al., 2000).

3.1.3 Modeling the pregnancy effect

The other important component of modeling milk yield for reproductive analysis is the pregnancy effect, as its onset is shifted when the calving interval is changed. Danell (1982b) reports that the pregnancy effect consists of an average milk yield losses of 3 to 5 kilograms per day beginning at approximately 100 days pregnant. Oltenacu et al. (1980) further reported that the additional milk yield decline is an additive effect.

The pregnancy effect can be incorporated using values from the literature, or it can be measured from the milk yield data. Hady (1994) incorporated the results of Oltenacu's (1980) examination of the negative relationship between partial lactation yields and days open to arrive at parameters for the lactation curves in his partial budget model. Van Arendonk (1985) used adjustment factors based upon Danell (1982b) for his insemination and replacement model.

For individual herds, measuring the pregnancy effect when fitting their milk yield data may be more accurate, since the magnitude of the pregnancy effect may not be constant across herds. When using linear lactation curve models, investigators commonly represent the pregnancy effect with an additional parameter for days pregnant. For nonlinear models, Coulon et al. (1998) proposed the following additive modification to account for the pregnancy effect:

(19) $PE_t = a\ (w_p - 18)\ e^{-bwp}$,

where PE_t = milk yield reduction on day t of lactation attributable to the effects of pregnancy, and

Wp = weeks pregnant.

For example, Perochon et al. (1996) incorporated Coulon's pregnancy effect and a similar season effect into the Morant model, creating a comprehensive model that he recommended for capturing individual variability in lactation curves.

3.2 Preliminary analysis: Individual lactation curves

The most commonly used lactation curve model, the Wood model, may not adequately capture the rate and shape of milk yield decline across herds and their management groups. The goal of the preliminary analysis is to determine if there is reason to believe that a flexible shape model would more accurately characterize the change in milk yield for a herd considering a reproductive management change.

3.2.1 Empirical lactation curve model

The LPM, from Grossman et al. (1999), was modified for use in this preliminary analysis. The LPM is a linear spline model that represents milk yield through lactation as three connected linear segments -- a linear ascent, a flat peak, and a linear descent. The modified model can capture two distinct segments of declining milk yield and an additional segment for additional decline in late stages of pregnancy. Modifications to the LPM for this analysis, summarized in Table 3.2 and depicted graphically in Figure 3.3, include:

- Adding a third knot (and corresponding fourth segment) to allow two phases of milk yield decline. This allows the model to represent a change in the rate of mid-lactation milk yield decline. Vargas (2000) used a similar three-knot version of the LPM in his evaluation study – the model fit ranked second in R^2, RSD, DW, and MAD against other common lactation curve models.

- Incorporating an additional knot for lactations that involve pregnancy – the last segment of the model, its timing based upon days pregnant rather than days in milk, allows a different rate of decline in late stages of pregnancy. Since nonpregnant cows have zero days pregnant throughout lactation, they will not display a fifth segment.

- Fixing the length of transition between segments (r1, r2, r3, r4) to one day. Forcing sharp transitions ensures clearly defined transitions between production phases. This restriction does not significantly reduce model fit (Grossman et al., 1999).

The resulting empirical model is of the form:

$$
\begin{aligned}
(20)\quad y_t = y_p + b_1 * (DIM_t - t_1) & - b_1 * \ln((e^{DIMt}+e^{t1})/(1+e^{t1})) \\
& + b_3 * \ln((e^{DIMt}+e^{t2})/(1+e^{t2})) \\
& + (b_4 - b_3) * \ln((e^{DIMt}+e^{t3})/(1+e^{t3})) \\
& + (b_5 - b_4) * \ln((e^{DPt}+e^{t4})/(1+e^{t4}))
\end{aligned}
$$

where y_t = milk yield (lbs.) on day *t* since calving,

y_p = peak yield,

b_j = slope of segment *j*, *j* = 1 to 5 ($b_2 = 0$), and

t_j = day *t* since calving of transition from segment *j* to *j+1*

DIM_t = days *t* since calving, and

DP_t = days pregnant on day t since calving.

As shown in Figure 3.3, the parameters of the model identify the rate of change of milk yield of each segment and the days in milk at which the rate of change changes. The b parameter represents the milk yield change (pounds per day) of the corresponding segment. The t parameters can be interpreted as the days in milk at the transition to the next segment.

3.2.2 Persistency measurements

Milk yield decline

Important properties of persistency are the rate of decline and the change in the decline rate – the first and second derivatives of the empirical lactation curve model. The modified LPM used in this analysis allows direct measurement of these characteristics to from model parameters, as shown in Table 3.3. Persistency, both before and after the effects of pregnancy begin, can be quantified using the slopes and transitions in the lactation curve identified by the modified LPM.

The modified LPM model used in this analysis depicts two decline rates (b_3 and b_4) that are constant in pounds per day. Both these b values are negative, as they represent the rates of milk yield change in pounds per day for their respective decline segments. The difference between the slopes of the decline segments (b_3-b_4) is the only change in decline rate that can be represented by this model. A positive value indicates that decline in later stages of lactation is faster than in earlier stages; vice versa for negative values. Thus, the rate of decline can be classified as:

- *Decreasing,* if b_3 is negative and $b_3 > b_4$,
- *Increasing* , if both b_3 and b_4 are negative and $b_3 < b_4$, or
- *Constant,* if the model failed to use the knot allowed for the segments prior to the pregnancy effect, thus depicting one segment of decline.

Pregnancy effect

Since the model allows an additional knot in pregnant cows, an additional decline rate can be represented for advancing stages of pregnancy. In pregnant cows, the difference between the slopes of the second decline segment (b_4) and final segment (b_5) represents the additional decline associated with advancing pregnancy, or the "pregnancy effect". Since non-pregnant cows are limited to a three knot model (days pregnant is zero for the entire lactation), only pregnant cows can display this additional change in decline rate. Both onset and magnitude of the pregnancy effect were measured for pregnant cows:

- O*nset* -- days pregnant at t_4, if $b_4 < b_5$ and the cow is pregnant greater than 100 days at t_4.
- *Magnitude* -- the difference in slope between the final segment (b_5) and the previous segment: $b_5 - b_3$ if constant decline, $b_5 - b_4$ otherwise.

Lactations in which the slope of the final segment (b_5) was less steep than the prior decline segment and (or) the accelerated decline began before 100 days pregnant were classified as not displaying a pregnancy effect. Rather, the final segment was considered an extension of the prior segment. The slope for the combined segment was then calculated as the weighted average of the two segments.

Peak yield

Although not a part of persistency, peak production defines the starting point for milk yield decline. It characterizes the tradeoff of early lactation milk production and late lactation when calving interval is changed and the starting point for milk yield decline. Peak yield, onset, and duration can be simply calculated from parameters of the modified LPM:

- *Peak yield* – defined as the parameter y_p.
- *Onset of peak yield* – defined as the days in milk at the beginning of peak yield, t_1.
- *Duration of peak yield* –number of days between onset of peak yield (t_1) and the beginning of milk yield decline (t_2), or the value of $t_2 - t_1$.

3.2.3 Data and statistical methods

This study used historical daily milk yield data from Michigan State University Teaching and Research Farm, a Holstein dairy farm in central Michigan, milking approximately 150 cows. The study included lactations that began after January 1, 1995 and ended before March 15, 1998. Milk yield at this facility averaged approximately 25,000 lbs/year over the period of the study. Although tie stall and free stall housing systems are used in this facility, no explicit feeding or production groups were defined (i.e., first lactation heifers were not separated from mature cows).

Because the results are ultimately intended for use in herd reproductive management analysis, cows in lactations that would likely be managed separately from the normal population were removed from the data set. Lactations with the following characteristics, each of which occurred in less than five percent of the herd, were excluded from the study:

- lactation length less than 200 days – these cows would not likely be part of the breeding herd, nor would they demonstrate lactation curve shape features examined here;
- spontaneous abortion after 100 days pregnant – termination of pregnancy once it has begun to depress milk yield would interfere with the milk yield decline patterns measured in the study;
- dry period of less than 45 days – extremely short dry periods do not provide sufficient time for normal mammary development prior to lactation;
- mastitis after 100 days in milk – since mastitis interferes with milk production during and after infection, the milk yield decline pattern for cows experiencing mid and late lactation mastitis does not reflect herd production; and
- recorded incidence of lameness and (or) miscellaneous diagnoses – these disorders interfere with milk production processes such that the lactation curve would be markedly different than the rest of the herd.

Each lactation is a time series of daily milk yields beginning on the day of calving (1 DIM) and continuing through the end of lactation. No differentiation was made between lactations terminated at dry off, for culling, or by death. The data set consisted of 362 lactations – 132 from first lactation heifers, and 230 from mature cows. Table 3.4 summarizes the descriptive statistics for this data set. Lactation length varied from 201 to 613 days.

The modified LPM model described in Section 3.4 was fitted to the daily milk yield in each lactation using nonlinear least squares methods in the STATA statistical package, version 6.0. Convergence was determined based on the change in relative change in residual sums of squares between iteration i and iteration i-1. The convergence criterion is met when the relative difference is less than 10^{-6}. If a maximum of 1000 iterations were exceeded, then the lactation failed to converge. Of the initial 362 lactations, 8 heifer lactations and 17 cow lactations failed to meet the convergence criteria, leaving 338 lactations (124 heifer and 214 cow) for the lactation curve shape analysis.

Although serial correlation of residuals is expected (Vargas, 2001) in the resulting lactation curve model, it was not corrected in the nonlinear models due to computational limitations. Comparison of regression results for the Wood model before and after correction for first-order serial correlation indicates that the parameters before and after correction are very similar for all management groups. Figure 3.4 illustrates the predicted lactation curve for heifers in the data set with and without correction for serial correlation. The cumulative difference between the two sets of parameters to 365 days in milk is 46.5 pounds, or 0.20% of the total lactation production. The difference between the models at 365 days in milk is 0.41 lbs or 0.89% of milk yield on day 365. Thus, failure to correct for first order serial correlation in the nonlinear regressions models is not expected to affect milk yield estimates based upon the results. The remaining serial correlation does, however, prevent reliable formal hypothesis testing.

Lactation curve shape measures were calculated for each lactation from regression results. For most lactations, this involved the simple calculations from parameters described in Section 3.2.1. In lactations where one or more knots (segments) was not used by the model in the course of regression, other model parameters from the regression results did not reflect the conceptual definitions in Section 3.2.2 (e.g., positive b value for a downward sloped segment). However, milk yield values predicted by the model were consistent with the typical lactation curve shape. As such, the lactation curve shape parameters described in Section 3.2.2 were calculated from predicted milk yields rather than the regression results.

3.2.4 Preliminary analysis results and discussion

Herd results

The modified LPM captured between 45 and 97% of variation in daily milk yields over individual lactations that converged. The average R^2 value was 0.80 (SD = .11). All cow lactation curve results demonstrated the expected right skewed pattern with clear ascent, peak, and decline. Table 3.5 summarizes the mean regression results across all lactations in the herd.

Persistency values showed a high degree of variation across the herd, with large standard deviations relative to the mean. The largest part of the herd (39.6%) showed a decrease in decline rate (i.e., the second decline segment was flatter than the first). Slightly fewer (31.4%) demonstrated a single segment decline (constant decline rate). Only 29.0% showed an increasing rate of decline, with milk yield declining faster at the end of lactation. Those with a decreasing rate of decline had a larger average change (a reduction of 0.65 lbs decline per day) than those showing an increasing rate of decline (an additional 0.28 lbs decline per day).

The average peak yield was 96.2 pounds, continuing from 32 to 94 days in milk. About half (55.5%) of the lactations in which a pregnancy occurred showed an accelerated decline in milk yield in late pregnancy. Across these lactations, decline in the second segment after peak was 0.47 pounds per day faster than in the segment following peak yield. The onset of the observed pregnancy effect was often later than found in previous studies (100-125 days pregnant) with the mean value of 156 days pregnant. Timing values (days in milk) for both peak production and the pregnancy effect had large standard deviations relative to their means. The standard deviations for peak yield and the size of pregnancy effect were much smaller.

Results by management group

Results indicate apparent differences in persistency, as well as characteristics of peak yield and the pregnancy effect, across management groups. Tables 3.6 and 3.7 show the persistency measures for heifers and cows, respectively, by season of calving.

Heifer vs. Cow

Heifers typically demonstrated later, lower, and longer peak yields than cows. Indeed, some heifer lactation curves did not demonstrate a distinct peak in production, but rather remained flat through most of lactation and declined only at the end of lactation. Where the average heifer peak yield was 78 pounds per day beginning at 33 days in milk and continuing for 81 days, the average cow peak yield was 107 lbs / day beginning at 27 days in milk and lasting only 51 days. More heifers than cows (69% vs. 48%) displayed an accelerated milk yield decline in late stages of gestation. The mean acceleration for heifers (an additional 0.41 lbs of daily milk yield loss) was slightly smaller than for cows (an additional 0.51 lbs per day), although the cow values varied more widely.

Season of calving

Season of calving influences persistency as well as peak production. Differences in peak and persistency reflect the different lactation stages at which the season of calving groups experience summer heat stress and the resulting depression in milk yield. Mean peak yields for heifers calving in the summer and fall are smaller and later in lactation than winter and spring-calving heifers. Cows calving in summer and fall would experience summer heat stress in early lactation. Decreasing decline rates are significantly more prevalent in cows calving in the fall and heifers calving in winter. Summer milk yield depression affects these cows in mid lactation, allowing recovery to follow in late lactation. In these cases, it is likely that the first decline segment represents the depression, the second depicts reduced decline associated with recovery.

Regression results from this empirical model may not be as accurate in projecting the extension of lactation for reproductive analysis when the lactation is affected by seasonal milk yield depression. Like the decline segments, observed pregnancy effects for some cows appear to be confounded with milk yield depression occurring in the summer months. The high "pregnancy effect" observed for winter calving heifers and cows may also reflect the response to summer heat stress, as late gestation occurs in the summer months.

Seasonal milk yield depression is also linked to cases such as that shown in Figure 3.5 This winter-calving heifer shows a sharp decline in mid lactation consistent with milk yield depression resulting from summer heat stress. The positively sloped second segment of decline likely represents the milk yield recovery afterward. This pattern was common in winter and spring calving cows and heifers. If this increasing segment were extended to represent longer lactations associated with an extended calving interval, an artificially high projection of the milk yield change results. In reality, once recovery from the summer milk yield depression is complete, milk yield would resume its natural decline. Whether this new rate of decline is greater or less than the original decline rate (prior to summer heat stress), however, is not known.

Results of the preliminary analysis are consistent with the hypothesis that variation in lactation curve shape across management groups is more adequately reflected with a flexible functional form. Further analysis is required to examine the degree to which lactation curve models reflect herd management group milk yields and the implications of lactation curve model selection on reproductive management decision analysis. The following analysis looks at the results of fitting other lactation curves to this data.

3.3 Pooling by management group

An accurate projection of the milk yield change associated with a change in reproductive performance is a critical component in reproductive management decision analysis. A manager can fit the herd milk yield data with a lactation curve to quantify the expected change associated with the delay in pregnancy and subsequent lengthening of lactation. (Note: The effects of the change in lactation frequency are determined in the reproductive model.) When considering herd reproductive management in groups, a lactation curve assessment for each management group is required.

Eight management groups established for this analysis by parity and season of calving. Because of their fixed shapes, lactation curves commonly used may not adequately represent the differences in the lactation curve across these management groups in a herd. The goal of this section is to establish a lactation curve for each management group using various lactation curve models from the literature. The lactation curve model results can then be incorporated into the herd reproductive management decision analysis to determine whether more complicated nonlinear models provide different results than the more commonly used Wood model.

3.3.1 Empirical lactation curve models

Four lactation curve models were selected for the functional form of the relationship between days in milk and milk yield by management group – the Wood model, the LPM (spline) model from the preliminary analysis, a three-knot LPM model from Vargas et al. (2001), and the diphasic model. The Wood model is the most commonly used fitted lactation curve. The extended LPM and diphasic models were recommended by Vargas (2001) as the empirical lactation curve models with best fit for milk yield through lactation. The hyperbolic tangent function in the diphasic model was converted to the mathematically equivalent exponential form to facilitate statistical analysis.

A pregnancy effect term was added to each lactation curve model to allow the differences in the onset of pregnancy associated with each calving interval to be represented in the reproductive analysis. The Wood model was included both with and without a pregnancy effect term, since both have been used in reproductive models. The pregnancy effect for the Wood model, in logarithmic form, is represented an additional parameter that results in a multiplicative effect on milk yield, as in Hady et al. (1994). In the spline models, the pregnancy effect is represented with an extra segment in the model. Coulon's (1998) proposed pregnancy effect, shown in equation (19), is used with the diphasic model. The onset of the pregnancy effects for the Wood and diphasic models were fixed at 125 days pregnant, consistent with Danell (1982b) and Coulon (1998).

The resulting empirical lactation curve models were:

(21) Wood: $\text{Ln } y_t = a + b \ln DIM_t + c\, DIM_t;$

(22) Wood (PE): $\ln y_t = a + b \ln DIM_t + c\, DIM_t + d\, DP_t$;

(23) LPM5:

$$
\begin{aligned}
y_t &= yp + b_1 * (DIM_t - t_1) \\
&- b_1 * \ln((\exp(DIM_t) + \exp(t_1)/(1+\exp(t_1)) \\
&+ b_3 * \ln((\exp(DIM_t) + \exp(t_2)/(1+\exp(t_2)) \\
&+ b_4 * \ln((\exp(DIM_t) + \exp(t_3)/(1+\exp(t_3)) \\
&+ b_5 * \ln((\exp(DP_t) + \exp(t_4)/(1+\exp(t_4));
\end{aligned}
$$

(24) LPM4:

$$
\begin{aligned}
y_t &= yp + b_1 * (DIM_t - t_1) \\
&- b_1 * \ln((\exp(DIM_t) + \exp(t_1)/(1+\exp(t_1)) \\
&+ b_3 * \ln((\exp(DIM_t) + \exp(t_2)/(1+\exp(t_2)) \\
&+ b_5 * \ln((\exp(DP_t) + \exp(t_4)/(1+\exp(t_4)); \text{ and}
\end{aligned}
$$

(25) Diphasic:

$$
\begin{aligned}
y_t &= a_1 b_1 * [1-((\exp(2b_1(DIM_t - c_1)-1)/(\exp(2b_1(DIM_t - c_1)+1)] \\
&+ a_2 b_2 * [1-((\exp(2b_2(DIM_t - c_2)-1)/(\exp(2b_2(DIM_t - c_1)+1)] \\
&+ a_p * (DP_t - 125) * \exp(-b_p * AdjDP_t).
\end{aligned}
$$

For all models,

y_t = daily milk yield for cow i in lactation day t,

DIM_t = days since calving on day t of lactation

DP_t = days since conception on day t,

$AdjDP_t = DP_t - 125$, days after the expected pregnancy effect onset at 125 days pregnant, and

a, b, c, etc. = estimated parameters.

3.3.2 Data and statistical methods

The data set used in the individual lactation analysis, consisting of daily milk yield data from the Michigan State University dairy herd, was also used in this analysis. To more fully represent the entire herd, most lactations excluded from the preliminary analysis were included here. However, incomplete lactations (<200 days) were not included in this analysis. In addition, extremely long lactations (greater than 425 days) were truncated to prevent undue influence of the late lactation milk yields from the few extended lactations on the estimated lactation curve parameters. The data set consisted of panel data, with days in milk as the time series variables and lactation as the cross-sectional variable. The data set contained 334 lactations, ranging in length from 200 to 425 days in milk, as dictated by the exclusion criteria from the preliminary analysis.

Pooling of lactations by management groups

Using separate parameter sets to represent groups of cows with different characteristics is a common method of representing management variables. This method is used primarily effective for characteristics that affect multiple parameters of the lactation curve but not the underlying functional form. Indeed, heifer lactation curves are commonly estimated separately from mature cows, such as in Vargas (2000) and Hady (1994). Following this method, data sets were separated and lactation data pooled into eight management groups – two parity groups each subdivided into four season of calving groups. Summary statistics for each management group are summarized in Table 3.8. The following criteria were used in pooling:

Parity:

- Heifers Parity = 1
- Cows Parity = 2+

Season of calving:

- Winter — Calved between December 1 and February 28
- Spring — Calved between March 1 and May 31
- Summer — Calved between June 1 and August 31
- Fall — Calved between September 1 and November 30

Pooling of observations across time

Within management group, daily milk yields (to 425 days in milk) for all lactations were used in this analysis. A dummy variable for each lactation was incorporated into the lactation curve models. Thus, individual lactations were differentiated with a scale parameter, under the assumption that persistency for all lactations in each group come from the same population.

The general form of the resulting lactation curve model was:

(26) $Y_{it} = f(DIM_t) + g(DP_t) + a_i\ COWID_i + u_{it}$,

where y_{it} = milk yield for cow i in mgmt group j on DIM t,

$f(DIM_t)$ = relationship of milk yield on DIM_t to days in milk on day t,

$g(DP_t)$ = relationship of milk yield on DIM_t to days pregnant on day t,

a_i = deviation of milk yield for cow i from the group mean,

$COWID_i$ = categorical variable representing cow i, and

u_{it} = error term for cow i on day t.

Regression methods

Each lactation curve model was fitted using pooled group data in STATA version 6. For each set of pooled milk yield data, milk yield was regressed on days in milk and days pregnant using least squares methods for each of the lactation curve functional forms. Regressions of the Wood models, which are linear in parameters, were corrected for first-order autocorrelation using the Prais-Winsten transformed regression estimator, performed for the value that minimized the sum of squares of the transformed equation. The milk yield observations were assumed independent across lactations but not within, and so the Huber/White estimator of variance was used. The nonlinear LPM and diphasic models were regressed using nonlinear least squares methods, using the same methods as the preliminary analysis. As discussed in Section 3.2.3, serial correlation was not corrected in the nonlinear models, but the residual serial correlation is not expected to affect the parameter results.

3.3.3 Results and discussion

All lactation curve regressions for all management groups converged. Evaluation of the models was based upon the R^2 statistic and RMSE, which varied across model, management group, and stage of lactation. R^2 and RMSE were calculated from the predicted data for milk yield (pounds per day). For the entire lactation, R^2 values ranged from 0.43 to 0.74. Tables 3.9 and 3.10 show the R^2 and RMSE of each lactation curve model for each management group in the various stages of lactation for heifers and cows, respectively. Stages of lactation were defined by days in milk, as in Vargas et al., (2000).

Fit was generally better in the middle stages of lactation than either the beginning or end. In general, the nonlinear models fit better than the linear Wood models, but none of the curves showed the best fit for all management groups in all stages of lactation. All LCMs except LPM5 had at least one stage of lactation for one management group with a negative r-squared value.

Milk yield projections for each management group were calculated using the group mean value for the dummy variable for lactation ($COWID_i$), combined with other regression results from the pooled group data. Figures 3.6 to 3.13 depict the fitted curves for each management group. Selected persistency measures for each lactation curve model are shown in Table 3.11 (heifers) and 3.12 (cows). Values in these tables were calculated for lactations with pregnancy beginning at 125 DIM. Although persistency is depicted differently across lactation curve models, the models showed similar milk yields through lactation. Differences in the rate of milk yield decline across lactation curve model are most prominent at the end of lactation.

The Wood model fit heifer lactations more consistently with the nonlinear models than it did cow lactations. The milk yields of heifer lactations were generally more persistent, which is consistent with the Wood model's depiction of milk yield decline. Compared to the nonlinear models, the Wood model did not fit lactations with more rapid and accelerating decline well. These characteristics were most common in cow lactations. In particular, the Wood model did not accommodate the sharp decline in milk yield that occurs in late lactation of winter and fall cows. When a pregnancy effect is incorporated, the model showed better fit, but the pregnancy effect reflected the summer heat stress and associated milk yield depression rather than milk yield reductions associated with reproduction. Shifting the onset of the pregnancy effect for changes in calving interval is not an accurate representation of the expected changes in milk yield for these cows.

Whether the improved fit of the nonlinear models is necessary for accurate reproductive management decisions requires further analysis. Tables 3.13 and 3.14 show the expected differences in cumulative lactation milk yields associated with different calving intervals. In Chapter 4, these milk yield projections are incorporated into the reproductive decision model from Chapter 2 and the results evaluated to determine if the differences in fit would influence herd reproductive management decisions.

Although the five-segment LPM model captured the variety of milk yield decline shapes apparent in the herd, its usefulness as the basis for lactation curve extension is questionable. All lactation curve models except LPM5 showed larger cumulative milk yields for longer calving intervals and declining differences between successively longer calving intervals. The LPM5 model depicted ranges of increasing milk production for some groups, which resulted in total milk yield projections that increase at an increasing rate with lengthening calving interval. As a result, LPM5 results will be excluded from the Chapter 4 analysis.

3.4 Summary and conclusions

The expected milk yield change associated with a change in reproductive performance is critical to valuing the changes in reproductive performance. Accurately calculating the expected change in milk yield requires a functional form for the lactation curve model. Lactation curve models currently used in reproductive analyses often do not allow for adequate variation in the shape of milk yield decline to describe a herd of cows – especially when subdivided into management groups.

A generalized form of the Lactation Persistency Model, designed to measure multiple milk yield decline rates, was fit to daily milk yields from individual lactations in a Michigan dairy herd. Results indicated apparent differences in persistency, defined as the rate(s) of decline and the change in decline rate, which support the possibility that parametric models with a fixed shape may provide inaccurate projections of the milk yield change associated with a change in the calving interval.

Milk yield data from the lactations used in the preliminary analysis were pooled into parity and season of calving management groups. Common lactation curve models – including the commonly used Wood model and recently proposed nonlinear models – were fit to the pooled data. All lactation curve models showed differences in lactation curve shape across management groups consistent with previous findings in the literature, including slower milk yield decline and lower peak yields for first lactation heifers than their mature counterparts and for summer versus winter calving heifers and cows.

Across management groups, the lactation curve models depicted persistency differently. These differences were more pronounced across mature cow groups than heifer groups. Extension predictions, too, appear different by lactation curve model. However, the statistical significance of these observations is not tested in this analysis due to residual autocorrelation in the nonlinear models. In Chapter 4, the effects of lactation curve model selection on reproductive management decision analysis are examined.

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Table 3.1. Comparison of fit across lactation curve models, from Vargas et al. (2000).

General measures of fit over all lactation.

	R2		RSD		DW		Cases where
	Mean	SD	Mean	SD	Mean	SD	DW > 0 [1]
Wood	0.957	0.03	0.870	0.22	0.56	0.27	23
Morant	0.973	0.02	0.660	0.17	0.86	0.42	16
Diphasic	0.987	0.01	0.480	0.13	1.74	0.44	1
LPM	0.985	0.03	0.420	0.26	1.79	0.60	2

Mean absolute deviation by stage of lactation [2]

	1-100 DIM		101-200 DIM		201-305 DIM		306+ DIM	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Wood	45.8	14.9	42.7	15.0	80.7	41.0	115.9	56.8
Morant	58.2	12.3	38.1	16.1	53.3	31.8	84.1	47.2
Diphasic	46.1	27.5	17.7	8.2	26.8	17.0	43.2	28.2
LPM	36.1	30.5	18.3	21.8	22.6	16.5	50.4	59.4

[1] Number of runs (of 26) with significant positive autocorrelation

[2] Mean absolute deviation is defined as the sum of daily absolute deviations for the period specified.

Table 3.2. Modifications to the Lactation Persistency Model.

Model	LPM	Reduced LPM	Three-knot LPM	Four-knot LPM
Authors	Grossman, 1999	Grossman, 1999	Vargas, 2000	
Segments	3	3	4	5 if pregnant, 4 if not
Transition length	r's not fixed	$r_1 = r_2 = 1$	r's not fixed	All r's = 1
Ascent	b_1 not fixed	$b_1 = y_P / t_1$	b_1 not fixed	b_1 not fixed
Peak	$b_2 = 0$	$b_2 = 0$	b_2 not fixed	$b_2 = 0$

Table 3.3. Persistency measures for the modified LPM.

Shape characteristic	Measurement criteria
Persistency	
First rate of decline	b3 pounds / day
Second rate of decline	b4 pounds / day
Decreasing decline rate	'Yes' if $b_3 < b_4$
Increasing decline rate	'Yes' if $b_3 > b_4$
Constant decline rate	'Yes' if middle knot is not used
Pregnancy effect	
Onset	t4 days in milk (if t4>100 DCC. If not, none)
Magnitude	b5 – b4 (if t_4 = onset. If not, appropriate b values.)
Peak	
Peak yield	yp pounds
Peak onset	t1 days in milk
Peak duration	t2 – t1 days

Table 3.4. General description of the dataset.

Herds	1	
Cows	179	
Lactations	362	
First lactation	132	
Second or later lactation	230	
Records	131,215	
Records per lactation	315	+/- 59.4
Lactation length	321	+/- 61.0
Daily milk yield	75.0	+/- 11.9

Table 3.5. Summary of regression results from individual lactation curve analysis.

	Frequency		Mean	StDev
Decline shape				
Decreasing	134	39.64%		
1st slope			(0.40)	0.472
2nd slope			0.41	1.003
Change			(0.65)	0.937
Linear	106	31.36%		
Slope			(0.23)	0.185
Increasing	98	28.99%		
1st slope			(0.28)	0.450
2nd slope			(0.56)	0.842
Change			0.28	0.657
Peak characteristics				
Yield (lbs/day)			96.2	20.75
Duration (days)			62	56.9
Begn			32	31.2
End (beg'n decline)			94	58.0
Pregnancy effect				
Total pregnant	281	83.1%		
Occurrence	156	55.5%		
Onset (DCC)			158	36.6
Acceleration (add'l lbs/day)			0.47	0.35

Table 3.6. Persistency measurements for first lactation heifers by season of calving.

	All heifers	Winter	Spring	Summer	Fall
	n = 124	n = 32	n = 29	n = 24	n = 39
Persistency					
Mean 1st slope	-0.17 +/- 0.28	-0.19 +/- 0.21	-0.17 +/- 0.10	-0.14 +/- 0.16	-0.17 +/- 0.43
Mean 2nd slope	0.03 +/- 0.54	0.42 +/- 0.78	-0.10 +/- 0.33	-0.17 +/- 0.34	-0.06 +/- 0.33
Mean Change	-0.20 +/- 0.59	-0.61 +/- 0.79	-0.07 +/- 0.33	0.04 +/- 0.30	-0.11 +/- 0.53
Decrease in decline rate	50 40%	21 66%	9 31%	8 33%	12 31%
Constant decline rate	41 33%	9 28%	10 34%	8 33%	14 36%
Increase in decline rate	33 27%	2 6%	10 34%	8 33%	13 33%
Peak characteristics					
Yield (lbs/day)	77.7 +/- 13.1	82.4 +/- 7.8	80.3 +/- 16.0	72.7 +/- 9.0	74.9 +/- 14.8
Duration (days)	80.9 +/- 66.5	78.7 +/- 51.7	71.9 +/- 83.1	92.3 +/- 72.4	82.4 +/- 61.1
Begn	39 +/- 35	33 +/- 34	37 +/- 31	42 +/- 41	44 +/- 36
End (beg'n decline)	120 +/- 64	112 +/- 51	109 +/- 81	134 +/- 62	126 +/- 59
Pregnancy effect					
Total pregnant	99 80%	25 78%	24 83%	19 79%	31 79%
Occurrence	68 69%	19 76%	13 54%	12 63%	24 77%
Onset (DCC)	161 +/- 33	155 +/- 32	171 +/- 31	155 +/- 34	163 +/- 33
Acceleration (add'l lbs/day)	0.41 +/- 0.31	0.60 +/- 0.39	0.30 +/- 0.19	0.38 +/- 0.29	0.34 +/- 0.27

Table 3.7. Persistency measurements for mature cows by season of calving.

	All cows	Winter	Spring	Summer	Fall
	n = 214	n = 72	n = 30	n = 38	n = 74
Persistency					
Mean 1st slope	-0.39 +/- 0.44	-0.50 +/- 0.68	-0.36 +/- 0.19	-0.34 +/- 0.19	-0.33 +/- 0.26
Mean 2nd slope	-0.24 +/- 0.88	-0.08 +/- 1.22	-0.21 +/- 0.31	-0.43 +/- 1.07	-0.29 +/- 0.39
Mean Change	-0.16 +/- 0.89	-0.42 +/- 1.22	-0.15 +/- 0.34	0.09 +/- 1.08	-0.04 +/- 0.34
Decrease in decline rate	84 39%	33 46%	12 40%	16 42%	23 31%
Constant decline rate	65 30%	16 22%	11 37%	11 29%	27 36%
Increase in decline rate	65 30%	23 32%	7 23%	11 29%	24 32%
Peak characteristics					
Yield (lbs/day)	106.9 +/- 16.4	109.9 +/- 14.1	102.0 +/- 12.0	106.0 +/- 16.9	106.4 +/- 19.1
Duration (days)	51.1 +/- 47.4	51.8 +/- 45.0	79.0 +/- 70.5	41.8 +/- 46.3	43.8 +/- 33.1
Begn	27 +/- 28	24 +/- 23	24 +/- 32	38 +/- 40	26 +/- 21
End (beg'n decline)	78 +/- 48	76 +/- 47	103 +/- 70	80 +/- 45	70 +/- 37
Pregnancy effect					
Total pregnant	182 85%	62 86%	24 80%	31 82%	65 88%
Occurrence	88 48%	34 55%	8 33%	15 48%	31 48%
Onset (DCC)	155 +/- 39	158 +/- 43	150 +/- 33	144 +/- 33	159 +/- 40
Acceleration (add'l lbs/day)	0.51 +/- 0.36	0.62 +/- 0.44	0.54 +/- 0.25	0.31 +/- 0.22	0.47 +/- 0.31

Table 3.8. General description of the dataset used in group analysis by management group.

HEIFERS	Winter	Spring	Summer	Fall
Cows	31	22	25	36
Lactations	31	22	25	36
Records	10,364	7,030	8,988	11,538
Records per lactation	334 +/- 51.7	320 +/- 48.8	360 +/- 55.3	321 +/- 48.7
Lactation length	335 +/- 51.9	321 +/- 48.2	364 +/- 59.6	323 +/- 47.6

COWS	Winter	Spring	Summer	Fall
Cows	72	35	38	77
Lactations	72	30	38	74
Records	22,454	11,587	11,682	22,809
Records per lactation	312 +/- 64.1	331 +/- 53.4	307 +/- 75.9	296 +/- 55.9
Lactation length	324 +/- 73.6	333 +/- 52.9	311 +/- 76.3	306 +/- 53.0

Table 3.9. R-squared (R2) and root mean square error (RMSE) for heifers by season of calving and stage of lactation.

		Wood		Wood PE		LPM5		LPM4		Diphasic	
DIM	obs	R2	RMSE	R2	RMSE	R2	RMSE	R2	RMSE	R2	RMSE
Winter											
1-60	2180	47.3%	10.33	48.0%	10.26	51.4%	9.91	51.0%	9.95	49.1%	10.14
61-100	1480	22.3%	8.96	20.9%	9.04	40.4%	7.85	40.2%	7.86	41.4%	7.78
101-200	3652	31.4%	9.94	32.9%	9.83	37.6%	9.48	33.3%	9.80	37.1%	9.52
200-305	3620	41.1%	8.54	40.1%	8.61	42.0%	8.48	41.5%	8.51	41.4%	8.52
305+	1231	43.9%	9.68	48.7%	9.25	41.9%	9.85	43.3%	9.73	38.2%	10.15
Spring											
1-60	2451	53.6%	13.62	53.4%	13.65	49.9%	14.14	49.9%	14.15	49.3%	14.23
61-100	1634	50.4%	9.83	50.5%	9.82	56.1%	9.24	56.5%	9.20	56.2%	9.23
101-200	3792	51.0%	9.28	51.0%	9.27	55.4%	8.84	55.5%	8.84	54.7%	8.92
200-305	3322	66.5%	8.19	66.5%	8.20	67.2%	8.11	66.7%	8.18	66.1%	8.25
305+	1455	46.2%	8.89	46.1%	8.90	46.1%	8.90	41.7%	9.26	44.7%	9.01
Summer											
1-60	1897	60.1%	10.01	60.5%	9.97	59.8%	10.05	60.4%	9.97	53.6%	10.80
61-100	1277	43.2%	9.13	43.3%	9.12	54.4%	8.19	53.9%	8.23	52.7%	8.34
101-200	3153	61.3%	7.49	61.0%	7.52	62.6%	7.37	61.5%	7.48	62.0%	7.43
200-305	2997	69.4%	6.50	69.6%	6.48	73.6%	6.04	72.6%	6.15	72.7%	6.15
305+	1624	62.9%	7.81	63.2%	7.78	67.6%	7.30	64.7%	7.62	67.0%	7.36
Fall											
1-60	3052	66.3%	8.92	66.6%	8.89	63.9%	9.24	63.9%	9.25	57.1%	10.08
61-100	2063	69.5%	7.04	70.7%	6.90	73.9%	6.51	73.8%	6.52	71.5%	6.81
101-200	4944	70.3%	6.73	70.3%	6.73	72.1%	6.52	72.1%	6.52	71.6%	6.58
200-305	4739	65.9%	7.53	66.1%	7.51	69.4%	7.14	69.3%	7.15	67.0%	7.41
305+	1532	42.1%	9.22	42.5%	9.19	43.8%	9.09	43.7%	9.09	38.7%	9.48

Table 3.10. R-squared (R2) and root mean square error (RMSE) for mature cows by season of calving and stage of lactation.

		Wood		Wood PE		LPM5		LPM4		Diphasic	
DIM	obs	R2	RMSE	R2	RMSE	R2	RMSE	R2	RMSE	R2	RMSE
Winter											
1-60	2180	19.3%	17.57	20.7%	17.42	41.8%	15.36	38.1%	15.83	24.6%	17.48
61-100	1480	16.1%	15.78	20.5%	15.36	23.7%	15.05	14.9%	15.89	23.4%	15.08
101-200	3652	45.9%	13.24	46.2%	13.21	39.8%	13.96	37.3%	14.25	39.5%	14.00
200-305	3620	52.4%	12.75	53.6%	12.59	40.6%	14.24	34.5%	14.95	37.1%	14.65
305+	1231	-4.3%	20.27	-5.6%	20.40	20.3%	18.45	-31.7%	23.71	20.5%	18.42
Spring											
1-60	2451	25.8%	18.04	24.7%	18.18	39.9%	16.55	40.8%	16.43	24.7%	18.54
61-100	1634	8.5%	16.14	7.2%	16.25	40.0%	13.07	38.0%	13.29	37.9%	13.30
101-200	3792	20.6%	16.23	22.6%	16.03	40.8%	14.02	36.3%	14.54	38.3%	14.31
200-305	3322	68.9%	11.34	69.2%	11.29	73.3%	10.50	72.5%	10.65	73.7%	10.43
305+	1455	46.6%	11.64	45.5%	11.76	50.2%	11.34	49.2%	11.46	49.1%	11.46
Summer											
1-60	1897	10.9%	21.10	15.3%	20.57	35.3%	18.40	33.0%	18.73	20.0%	20.47
61-100	1277	20.3%	17.38	23.3%	17.04	47.7%	14.07	43.2%	14.67	46.2%	14.28
101-200	3153	66.1%	12.09	66.8%	11.96	70.7%	11.23	68.3%	11.69	69.3%	11.51
200-305	2997	64.7%	10.73	64.7%	10.74	63.6%	10.90	64.2%	10.82	64.0%	10.84
305+	1624	14.1%	15.78	25.3%	14.71	60.2%	10.40	42.3%	12.52	44.4%	12.29
Fall											
1-60	3052	32.0%	17.50	32.1%	17.49	48.3%	15.56	47.5%	15.68	28.4%	18.30
61-100	2063	45.5%	14.53	45.5%	14.53	61.2%	12.26	60.6%	12.37	52.5%	13.57
101-200	4944	69.6%	11.45	69.9%	11.40	76.7%	10.03	75.9%	10.20	72.4%	10.93
200-305	4739	65.8%	10.69	65.7%	10.71	65.9%	10.68	65.2%	10.79	56.9%	12.00
305+	1532	19.9%	16.66	20.6%	16.59	31.7%	15.56	10.9%	17.78	-5.3%	19.32

Table 3.11. Selected persistency results for group lactation curve analysis for heifer lactations by season of calving and lactation curve model.

	Peak yield		Milk prodn				Daily rate of change (lbs)				Daily percent change			
	DIM	Lbs/day	100 DIM	200 DIM	305 DIM	365 DIM	100 DIM	200 DIM	305 DIM	365 DIM	100 DIM	200 DIM	305 DIM	365 DIM
Winter														
Wood	71	79.1	78.1	68.2	55.6	49.0	(0.06)	(0.12)	(0.12)	(0.11)	-0.08%	-0.17%	-0.21%	-0.22%
WoodPE	74	78.6	77.9	67.2	53.9	46.9	(0.05)	(0.13)	(0.12)	(0.11)	-0.06%	-0.19%	-0.22%	-0.24%
LPM5	57-79	84.1	84.1	70.6	62.0	51.4	(0.00)	(0.08)	(0.18)	(0.18)	0.00%	-0.11%	-0.28%	-0.34%
LPM4	55	82.5	80.6	70.3	59.5	53.2	(0.10)	(0.10)	(0.10)	(0.10)	-0.13%	-0.15%	-0.17%	-0.19%
Diphasic	70	83.8	80.9	66.9	59.8	51.5	(0.16)	(0.07)	(0.10)	(0.18)	-0.20%	-0.11%	-0.17%	-0.35%
Spring														
Wood	71	73.0	72.0	62.3	50.1	43.7	(0.06)	(0.12)	(0.11)	(0.10)	-0.08%	-0.19%	-0.22%	-0.23%
WoodPE	106	72.9	72.8	63.0	49.5	42.7	0.01	(0.13)	(0.12)	(0.11)	0.01%	-0.21%	-0.24%	-0.25%
LPM5	56	76.4	74.3	64.9	53.1	37.8	(0.09)	(0.09)	(0.19)	(0.31)	-0.13%	-0.15%	-0.36%	-0.81%
LPM4	58	76.6	74.8	64.6	52.1	39.4	(0.10)	(0.10)	(0.21)	(0.21)	-0.14%	-0.16%	-0.41%	-0.54%
Diphasic	69	78.4	75.2	64.6	53.3	42.8	(0.16)	(0.06)	(0.16)	(0.18)	-0.21%	-0.10%	-0.30%	-0.43%
Summer														
Wood	85	71.8	71.5	62.6	50.1	43.3	(0.03)	(0.12)	(0.12)	(0.11)	-0.05%	-0.19%	-0.23%	-0.25%
WoodPE	94	70.1	70.1	61.2	48.4	41.7	(0.01)	(0.12)	(0.12)	(0.11)	-0.01%	-0.20%	-0.24%	-0.26%
LPM5	58-88	72.3	72.3	64.8	54.6	43.4	(0.00)	(0.09)	(0.19)	(0.19)	0.00%	-0.14%	-0.34%	-0.43%
LPM4	58-106	72.0	72.0	64.9	52.3	44.0	(0.00)	(0.11)	(0.14)	(0.14)	0.00%	-0.17%	-0.27%	-0.32%
Diphasic	76	74.9	73.1	65.5	53.0	43.1	(0.12)	(0.05)	(0.17)	(0.15)	-0.17%	-0.08%	-0.32%	-0.36%
Fall														
Wood	80	72.2	71.7	62.3	49.6	42.8	(0.04)	(0.12)	(0.12)	(0.11)	-0.06%	-0.19%	-0.24%	-0.25%
WoodPE	94	74.6	74.5	64.7	50.7	43.5	(0.01)	(0.13)	(0.13)	(0.11)	-0.01%	-0.21%	-0.25%	-0.26%
LPM5	56-92	74.0	74.0	66.4	53.1	38.3	(0.00)	(0.09)	(0.27)	(0.24)	0.00%	-0.14%	-0.50%	-0.62%
LPM4	57-88	74.6	74.6	67.0	54.0	38.5	(0.00)	(0.09)	(0.26)	(0.26)	0.00%	-0.14%	-0.48%	-0.67%
Diphasic	74	77.0	75.3	67.6	52.9	44.7	(0.11)	(0.09)	(0.15)	(0.11)	-0.14%	-0.13%	-0.29%	-0.26%

Table 3.12. Selected persistency results for group lactation curve analysis for cow lactations by season of calving and lactation curve model.

	Peak yield		Milk prodn				Daily rate of change (lbs)				Daily percent change			
	DIM	Lbs/day	100 DIM	200 DIM	305 DIM	365 DIM	100 DIM	200 DIM	305 DIM	365 DIM	100 DIM	200 DIM	305 DIM	365 DIM
Winter														
Wood	44	103.8	94.5	68.0	45.1	35.2	(0.25)	(0.25)	(0.18)	(0.15)	-0.26%	-0.37%	-0.41%	-0.42%
WoodPE	48	103.1	96.1	72.7	50.5	38.9	(0.21)	(0.23)	(0.22)	(0.17)	-0.22%	-0.32%	-0.43%	-0.44%
LPM5	40	106.9	97.4	72.8	47.0	49.9	(0.25)	(0.25)	(0.11)	0.05	-0.25%	-0.34%	-0.23%	0.10%
LPM4	39	102.0	86.7	66.5	45.3	33.4	(0.20)	(0.20)	(0.20)	(0.20)	-0.23%	-0.30%	-0.44%	-0.59%
Diphasic	64	104.7	100.5	69.4	51.7	50.1	(0.22)	(0.29)	(0.07)	0.00	-0.21%	-0.41%	-0.13%	0.01%
Spring														
Wood	47	90.4	83.1	59.9	39.6	30.9	(0.21)	(0.22)	(0.16)	(0.13)	-0.26%	-0.37%	-0.41%	-0.42%
WoodPE	51	89.2	84.0	64.7	45.4	34.5	(0.17)	(0.19)	(0.21)	(0.16)	-0.20%	-0.30%	-0.45%	-0.46%
LPM5	46-63	95.9	94.0	65.5	57.0	52.1	(0.29)	(0.14)	(0.08)	(0.08)	-0.31%	-0.21%	-0.14%	-0.15%
LPM4	41	95.9	90.0	73.2	55.6	41.0	(0.17)	(0.17)	(0.17)	(0.27)	-0.19%	-0.23%	-0.30%	-0.67%
Diphasic	70	96.2	94.0	66.8	42.3	35.4	(0.14)	(0.31)	(0.15)	(0.08)	-0.15%	-0.46%	-0.36%	-0.24%
Summer														
Wood	48	96.3	89.2	65.6	44.3	35.0	(0.21)	(0.23)	(0.17)	(0.14)	-0.24%	-0.35%	-0.39%	-0.40%
WoodPE	51	94.9	89.4	68.8	48.4	37.2	(0.18)	(0.21)	(0.21)	(0.17)	-0.20%	-0.30%	-0.43%	-0.44%
LPM5	32	98.7	90.7	73.8	47.4	31.7	(0.14)	(0.25)	(0.26)	(0.26)	-0.15%	-0.34%	-0.55%	-0.82%
LPM4	42	98.7	91.0	69.9	47.8	35.1	(0.21)	(0.21)	(0.21)	(0.21)	-0.23%	-0.30%	-0.44%	-0.60%
Diphasic	69	94.9	93.4	73.0	46.5	35.7	(0.09)	(0.27)	(0.21)	(0.15)	-0.10%	-0.37%	-0.46%	-0.42%
Fall														
Wood	47	103.5	94.5	66.9	43.3	33.2	(0.26)	(0.26)	(0.19)	(0.15)	-0.27%	-0.39%	-0.43%	-0.45%
WoodPE	48	103.2	95.0	68.6	45.2	34.5	(0.24)	(0.25)	(0.20)	(0.16)	-0.25%	-0.37%	-0.44%	-0.46%
LPM5	45-54	104.8	100.1	72.7	44.1	35.5	(0.27)	(0.27)	(0.27)	0.26	-0.27%	-0.38%	-0.62%	0.74%
LPM4	46-48	104.8	98.5	73.0	46.3	31.0	(0.25)	(0.25)	(0.25)	(0.25)	-0.26%	-0.35%	-0.55%	-0.82%
Diphasic	66	100.9	98.8	74.0	42.0	28.7	(0.12)	(0.32)	(0.26)	(0.19)	-0.12%	-0.44%	-0.62%	-0.65%

Table 3.13. Difference in milk yield associated with various calving intervals for heifer lactations by season of calving and lactation curve model.

	12 mo CI milk yield	Difference in milk yield from 12 mo CI						Difference in milk yield from previous CI					
		13 mos	14 mos	15 mos	16 mos	17 mos	18 mos	13 mos	14 mos	15 mos	16 mos	17 mos	18 mos
Winter													
Wood	21,093	1,572	3,039	4,406	5,680	6,863	7,963	1,581	1,467	1,368	1,273	1,184	1,100
WoodPE	21,340	1,626	3,152	4,582	5,919	7,168	8,335	1,292	1,526	1,429	1,337	1,250	1,167
LPM5	22,662	1,793	3,427	4,902	6,218	7,376	8,374	1,430	1,634	1,475	1,316	1,157	999
LPM4	22,231	1,745	3,397	4,954	8,120	7,360	8,120	1,287	1,652	1,558	3,165	0	0
Diphasic	21,736	1,751	3,381	4,853	6,128	7,167	7,931	1,534	1,630	1,472	1,275	1,039	764
Spring													
Wood	19,508	1,442	2,781	4,022	5,171	6,235	7,218	1,541	1,339	1,241	1,150	1,064	983
WoodPE	19,531	1,463	2,829	4,104	5,291	6,395	7,421	1,272	1,366	1,274	1,187	1,104	1,026
LPM5	20,482	1,520	2,815	3,834	4,577	5,044	5,236	1,341	1,295	1,019	743	467	191
LPM4	20,441	1,484	2,778	3,882	6,052	5,519	6,052	1,360	1,294	1,104	2,170	0	0
Diphasic	20,464	1,537	2,917	4,131	5,182	6,078	6,833	1,327	1,379	1,214	1,051	896	754
Summer													
Wood	18,745	1,409	2,717	3,927	5,046	6,079	7,031	1,476	1,308	1,211	1,119	1,033	952
WoodPE	19,208	1,459	2,816	4,075	5,243	6,322	7,320	1,134	1,357	1,260	1,167	1,080	998
LPM5	20,011	1,567	2,966	4,197	5,260	6,155	6,883	1,682	1,399	1,231	1,063	895	727
LPM4	19,932	1,517	2,910	4,176	7,225	6,334	7,225	1,612	1,392	1,267	3,049	0	0
Diphasic	20,007	1,528	2,905	4,144	5,261	6,279	7,216	1,221	1,378	1,239	1,118	1,017	937
Fall													
Wood	19,858	1,475	2,841	4,103	5,267	6,339	7,326	1,351	1,366	1,262	1,164	1,072	986
WoodPE	19,270	1,444	2,786	4,031	5,183	6,250	7,234	1,236	1,342	1,245	1,153	1,066	985
LPM5	20,532	1,495	2,771	3,831	4,678	5,310	5,728	1,228	1,275	1,061	846	632	418
LPM4	20,726	1,522	2,812	3,871	5,655	5,292	5,655	1,300	1,290	1,058	1,785	0	0
Diphasic	20,639	1,531	2,937	4,239	5,457	6,611	7,717	1,175	1,406	1,302	1,218	1,154	1,106

Table 3.14. Difference in milk yield associated with various calving intervals for cow lactations by season of calving and lactation curve model.

	12 mo CI milk yield	Difference in milk yield from 12 mo CI						Difference in milk yield from previous CI					
		13 mos	14 mos	15 mos	16 mos	17 mos	18 mos	13 mos	14 mos	15 mos	16 mos	17 mos	18 mos
Winter													
Wood	23,265	1,581	3,006	4,288	5,439	6,470	7,394	1,581	1,425	1,282	1,151	1,032	924
WoodPE	23,584	1,292	2,434	3,441	4,328	5,109	5,796	1,292	1,142	1,007	888	781	687
LPM5	24,578	1,430	2,909	4,439	6,019	7,650	9,332	1,430	1,479	1,530	1,580	1,631	1,682
LPM4	22,607	1,287	2,391	3,314	4,054	4,613	4,989	1,287	1,105	923	741	559	377
Diphasic	24,602	1,534	3,040	4,547	6,075	7,637	9,245	1,534	1,507	1,507	1,527	1,562	1,608
Spring													
Wood	21,458	1,541	2,937	4,198	5,336	6,362	7,284	1,541	1,396	1,262	1,138	1,025	922
WoodPE	22,344	1,272	2,402	3,404	4,291	5,076	5,769	1,272	1,130	1,002	887	785	693
LPM5	23,521	1,341	2,457	3,349	4,015	4,457	4,674	1,341	1,116	891	667	442	217
LPM4	23,249	1,360	2,531	3,511	4,302	4,904	5,316	1,360	1,170	981	791	601	412
Diphasic	23,678	1,327	2,488	3,511	4,422	5,241	5,989	1,327	1,161	1,023	911	820	748
Summer													
Wood	19,905	1,476	2,815	4,027	5,120	6,106	6,994	1,476	1,339	1,211	1,094	986	888
WoodPE	20,649	1,134	2,135	3,017	3,794	4,475	5,074	1,134	1,001	882	776	682	599
LPM5	21,690	1,682	3,291	4,827	6,291	7,682	9,001	1,682	1,609	1,536	1,464	1,391	1,318
LPM4	21,970	1,612	3,072	4,382	5,541	6,549	7,407	1,612	1,461	1,310	1,159	1,008	857
Diphasic	22,508	1,221	2,336	3,372	4,353	5,293	6,205	1,221	1,115	1,037	980	940	912
Fall													
Wood	23,123	1,351	2,546	3,600	4,528	5,344	6,060	1,351	1,195	1,054	928	816	717
WoodPE	23,298	1,236	2,319	3,267	4,095	4,817	5,447	1,236	1,083	948	828	722	630
LPM5	24,693	1,228	2,243	3,401	4,797	6,430	8,303	1,228	1,016	1,157	1,396	1,634	1,872
LPM4	24,715	1,300	2,371	3,212	3,823	4,206	4,358	1,300	1,071	841	612	382	153
Diphasic	24,641	1,175	2,148	2,949	3,610	4,156	4,612	1,175	972	801	661	547	455

Figure 3.1. Milk yield effect of pregnancy and extended calving interval (delayed pregnancy).

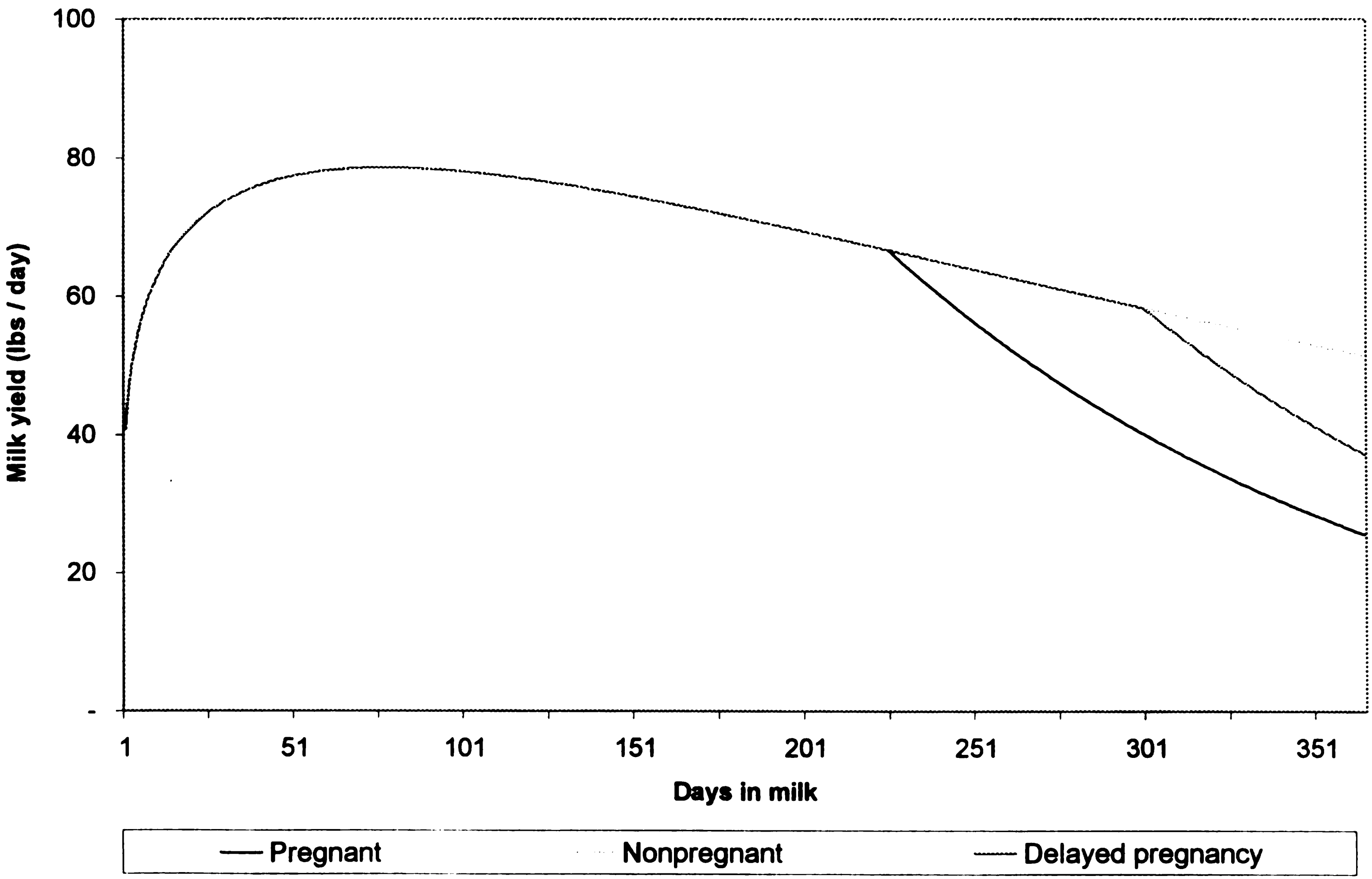


Figure 3.2. Depiction of lactation by Wood, Morant, Diphasic, and LPM models

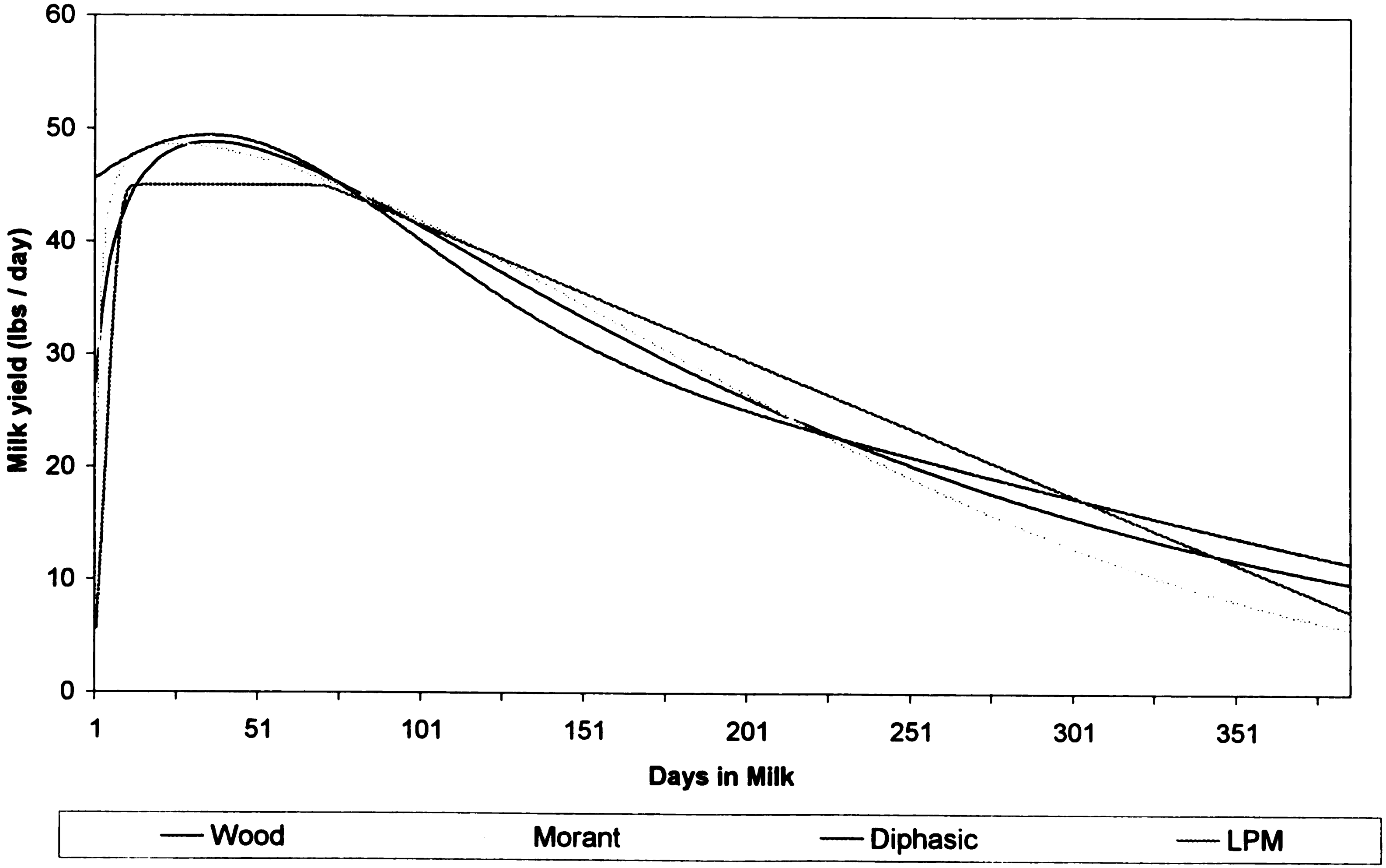


Figure 3.3. Lactation persistency model and the four-knot LPM used in this study.

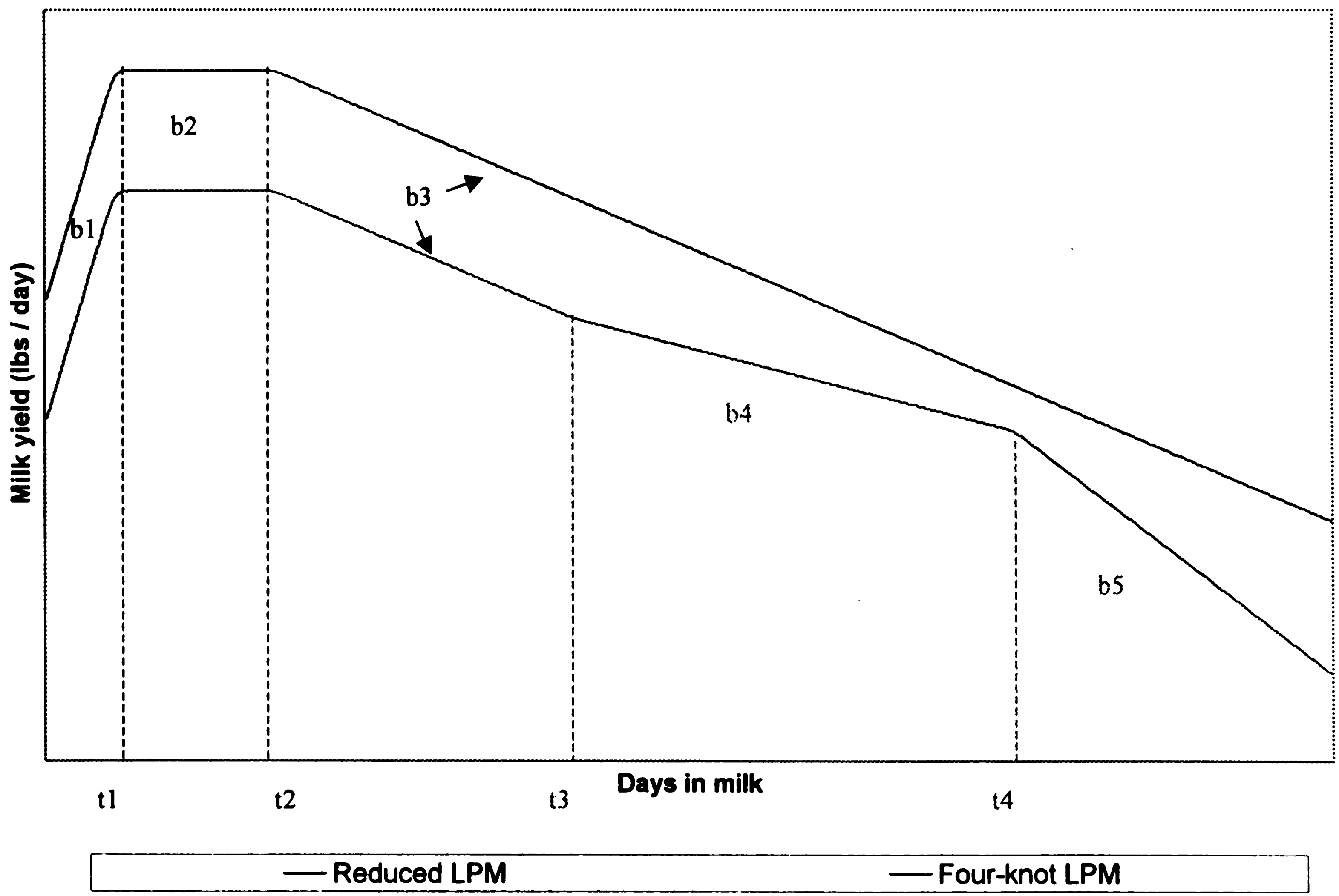


Figure 3.4. Comparison of Wood lactation curve regression results with and without correction for first degree serial correlation.

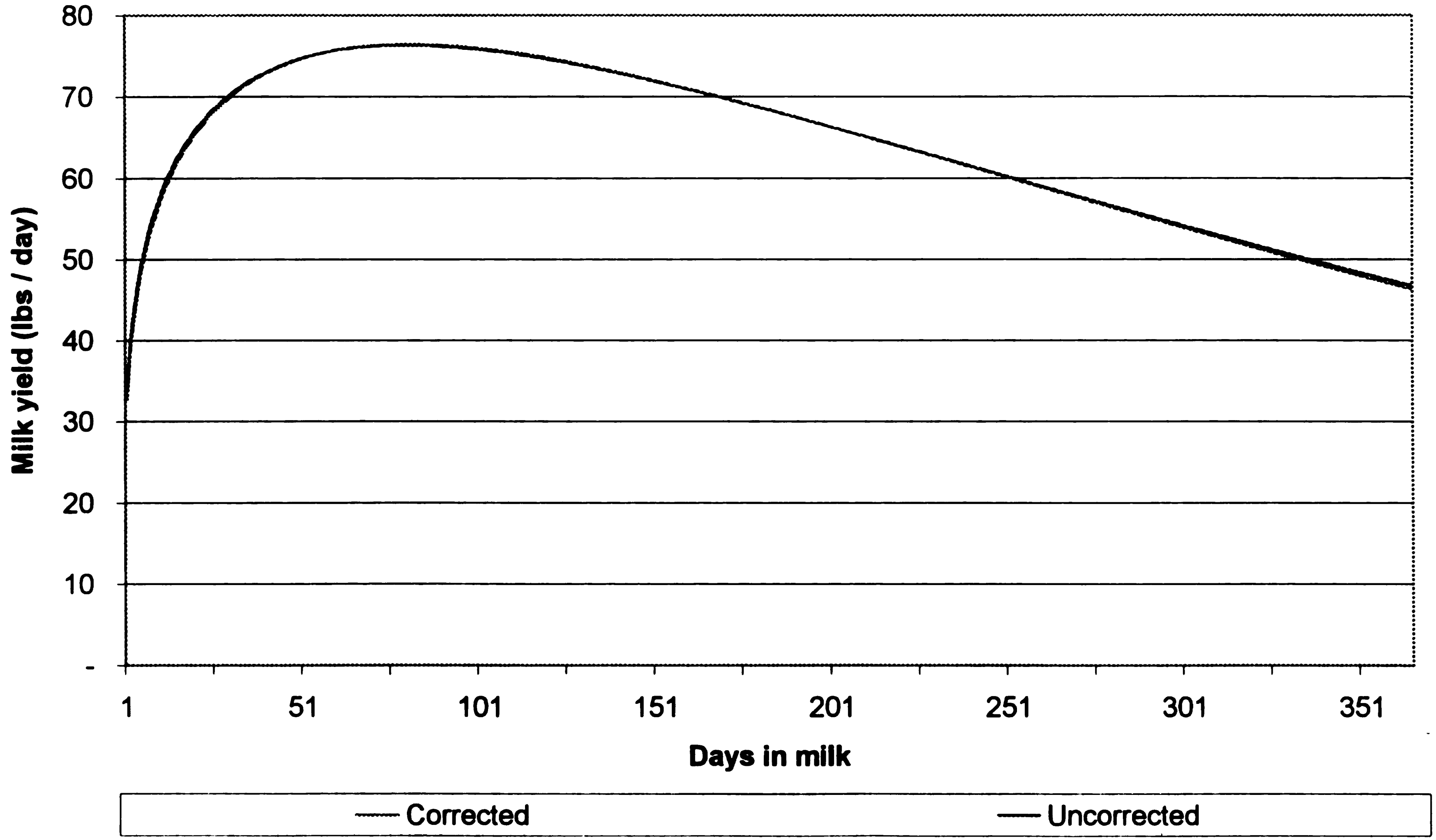


Figure 3.5. Lactation curve affected by seasonal milk yield depression.

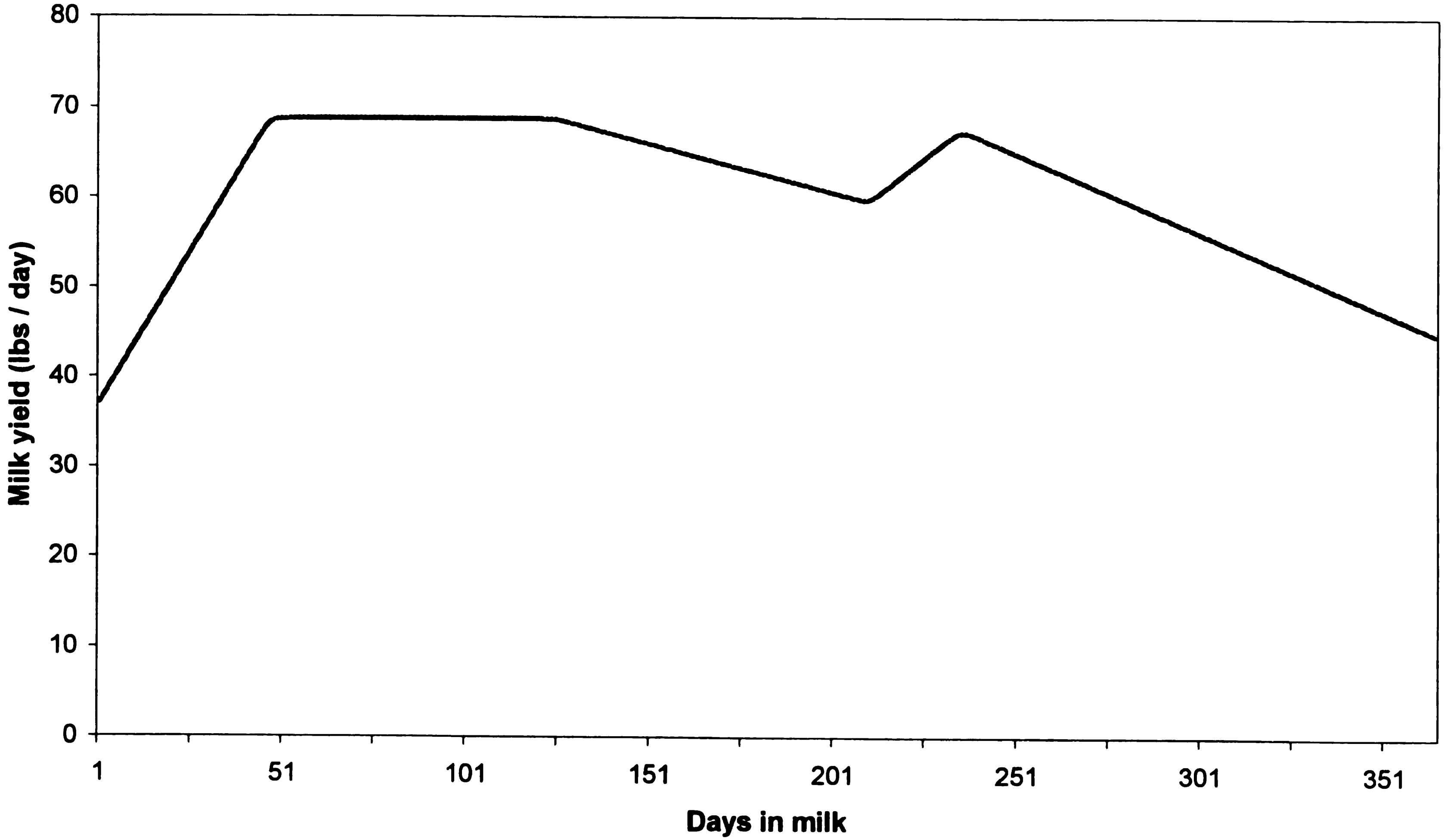


Figure 3.6. Projected milk yields for first lactation heifers calving in the winter.

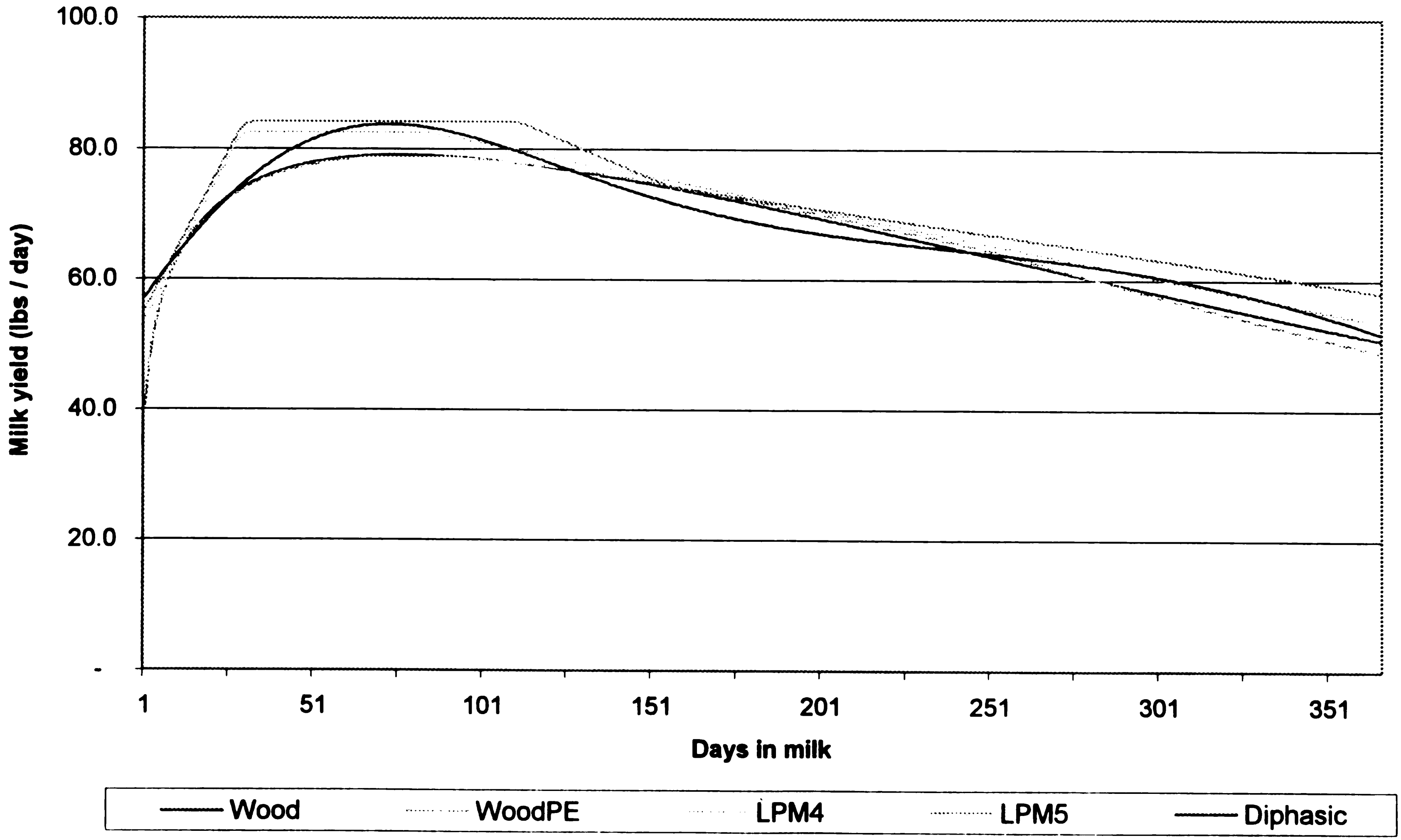


Figure 3.7. Projected milk yields for first lactation heifers calving in the spring.

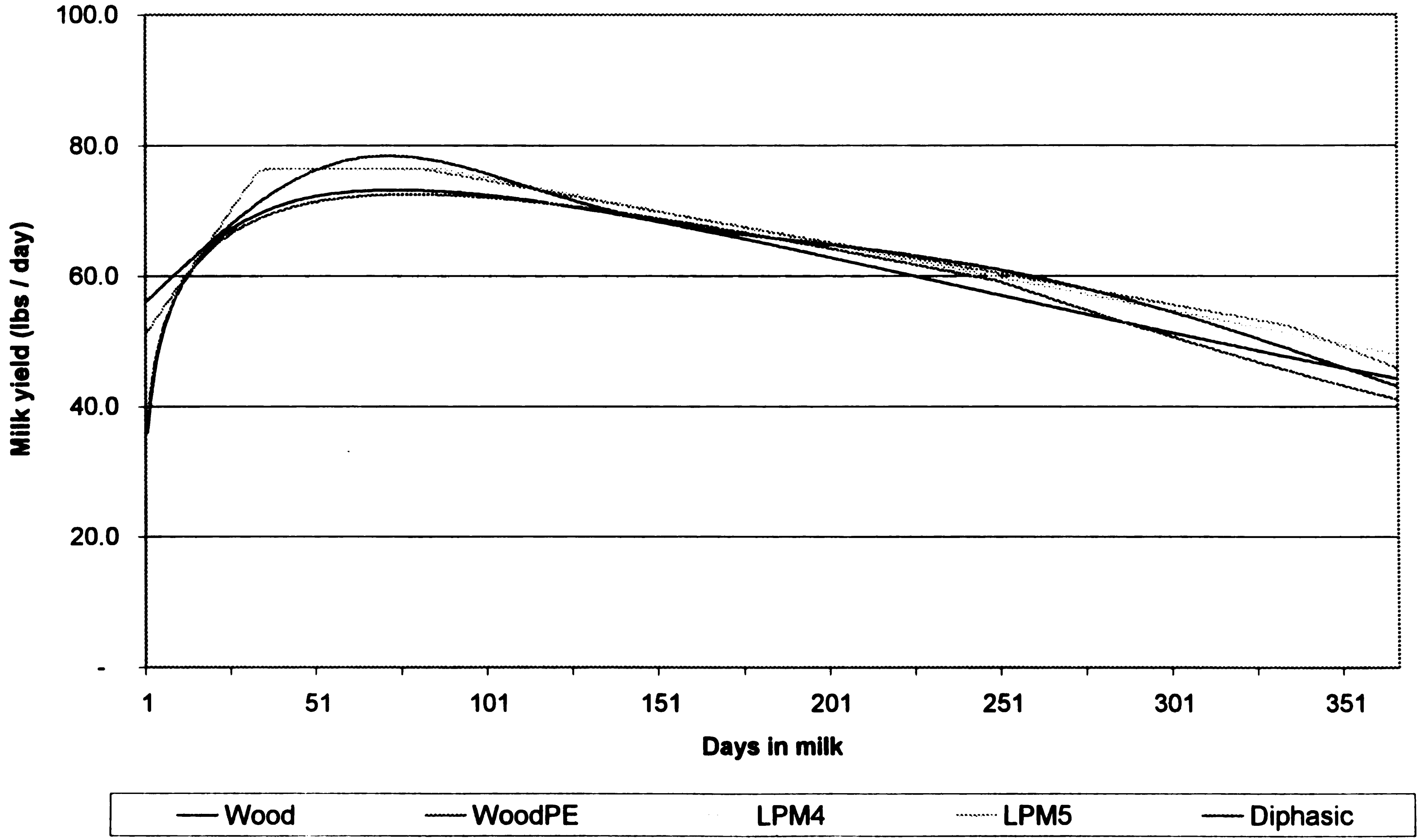


Figure 3.8. Projected milk yields for first lactation heifers calving in the summer.

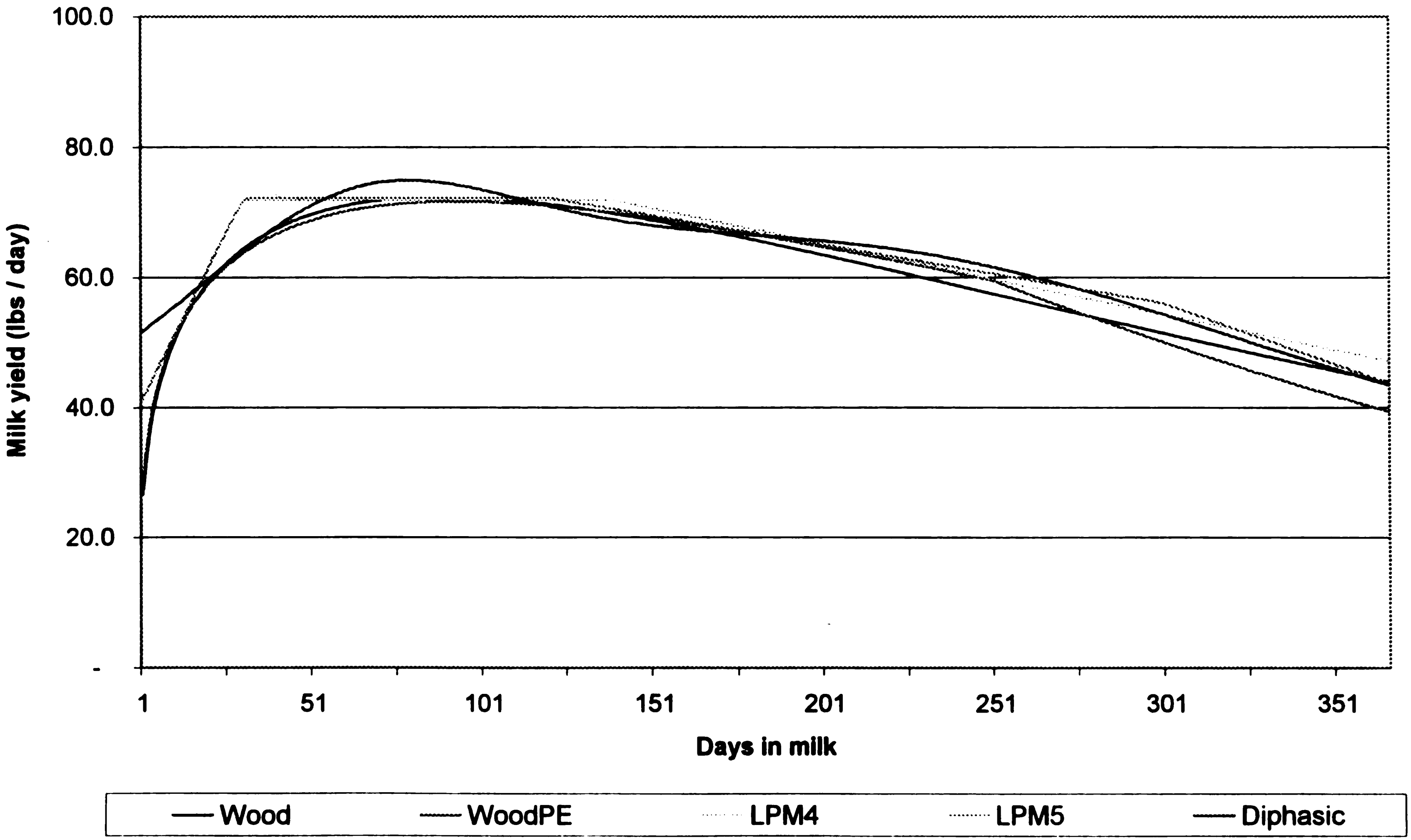


Figure 3.9. Projected milk yields for first lactation heifers calving in the fall.

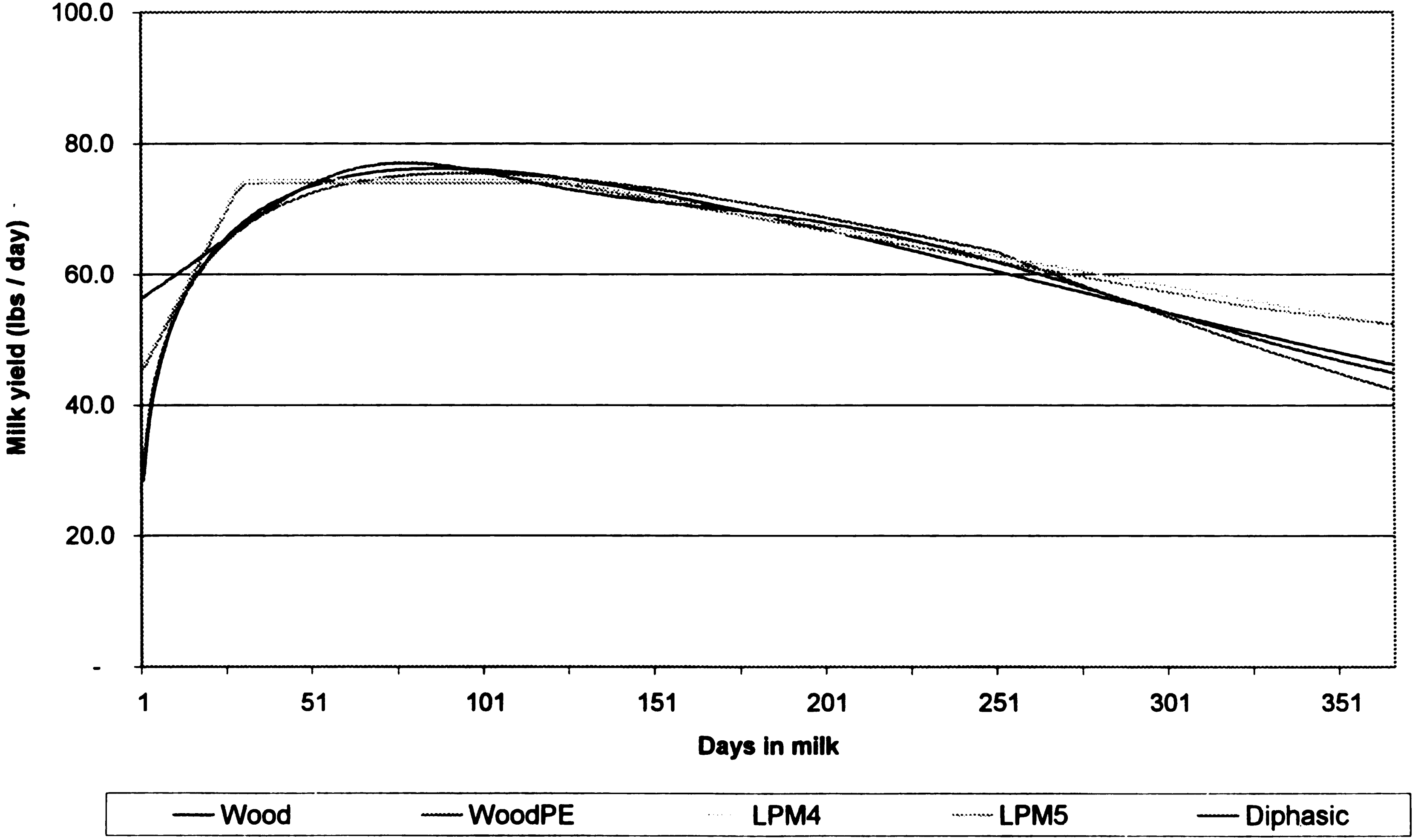


Figure 3.10. Projected milk yields for cows calving in winter.

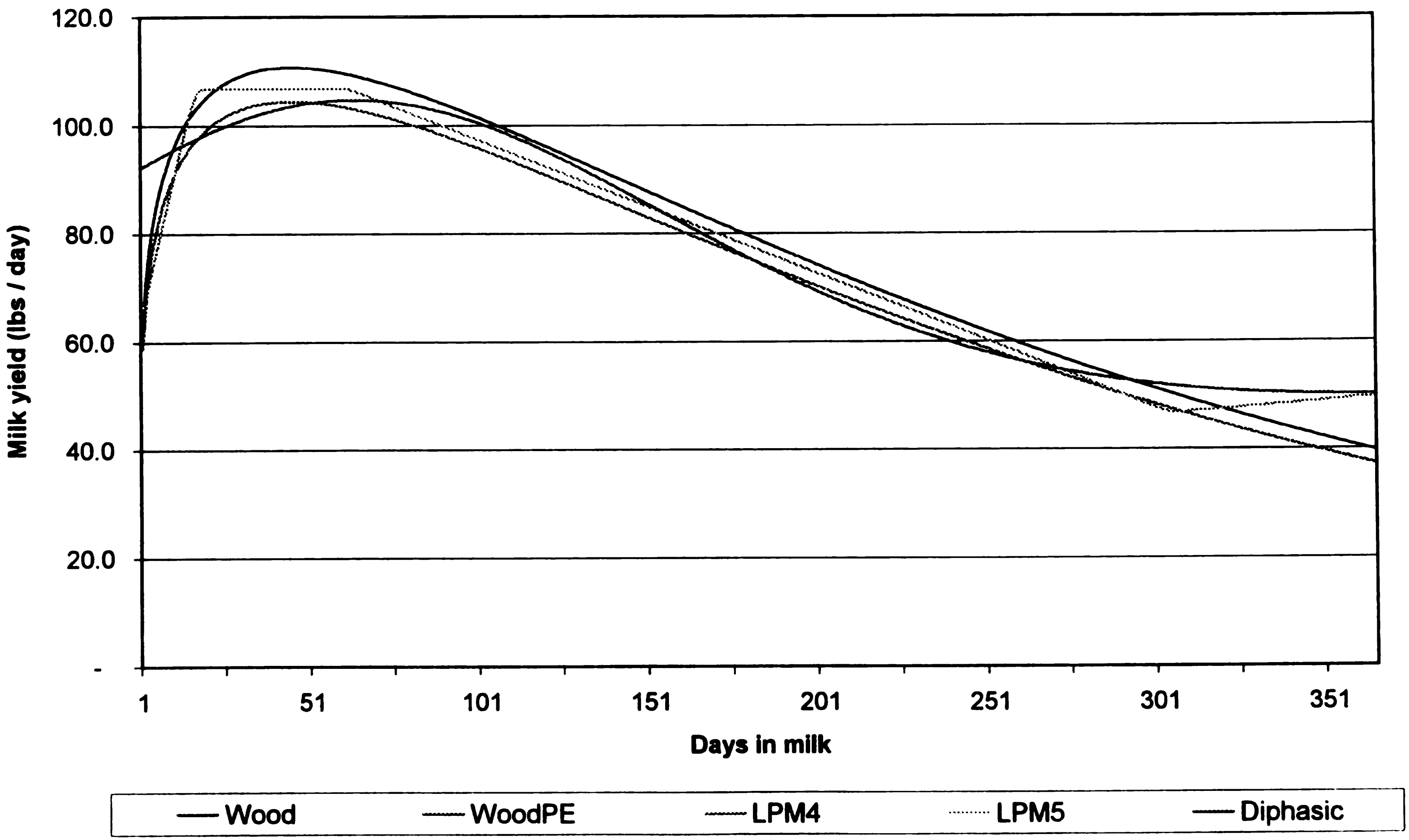


Figure 3.11. Projected milk yields for mature cows calving in spring

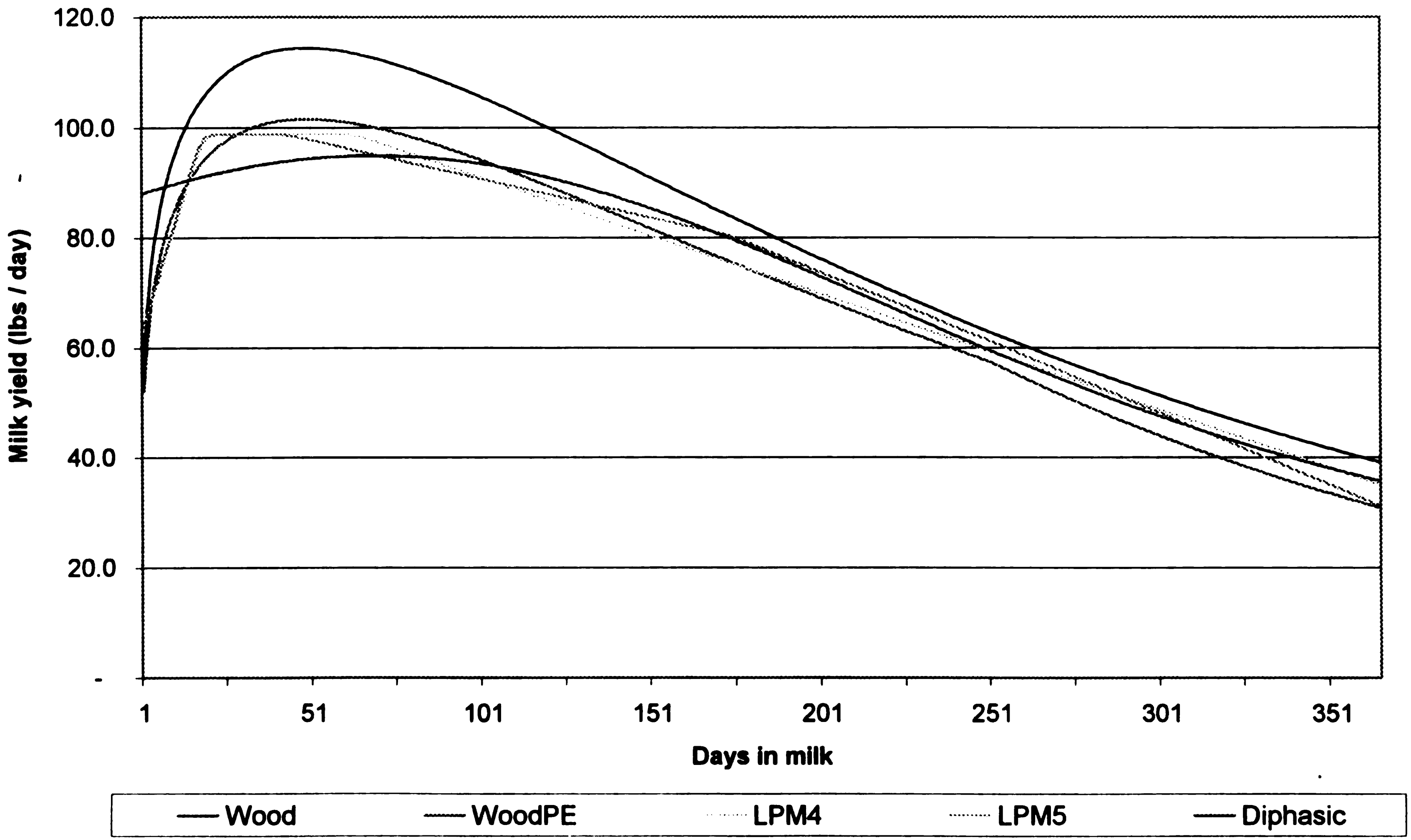


Figure 3.12. Projected milk yields for mature cows calving in summer

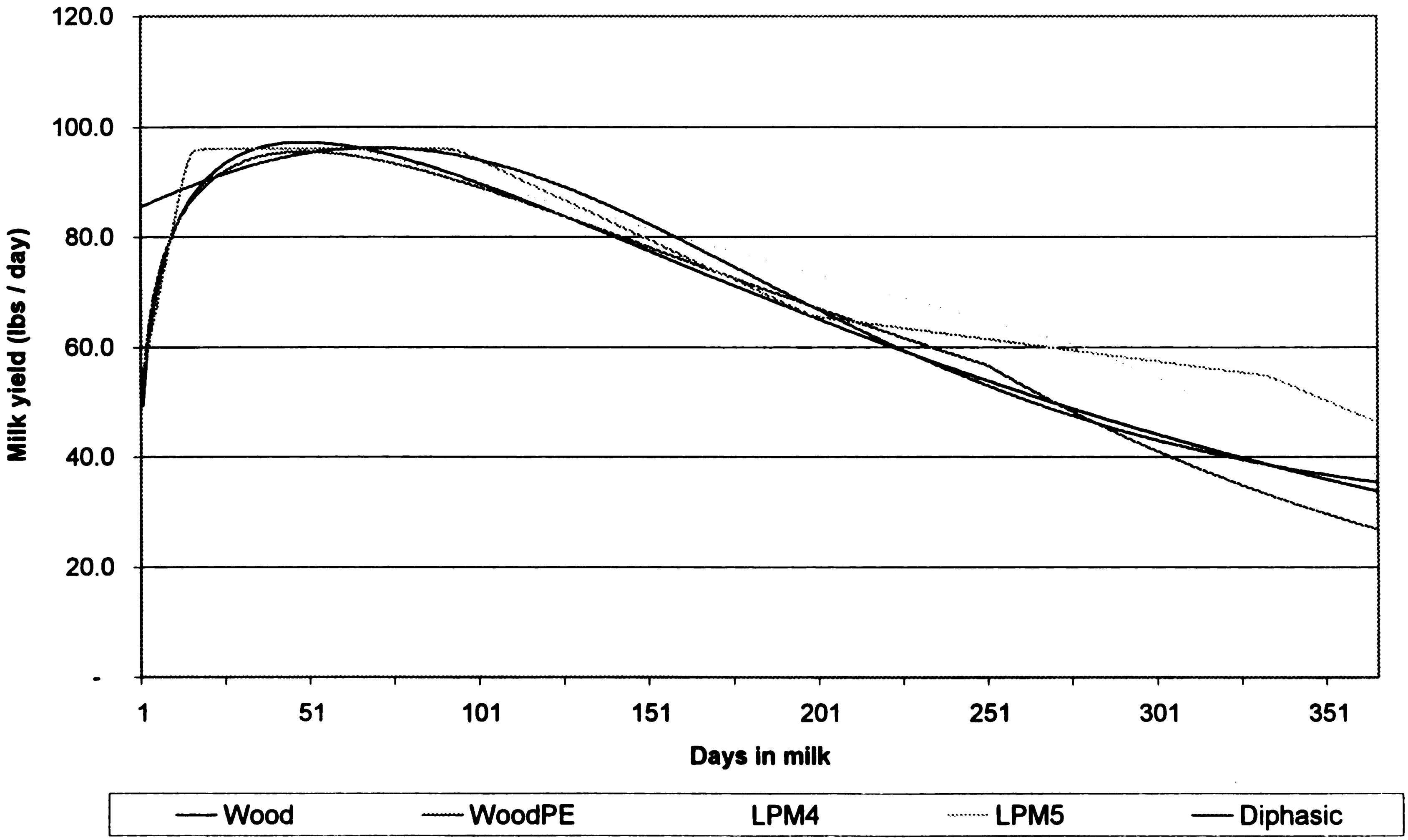
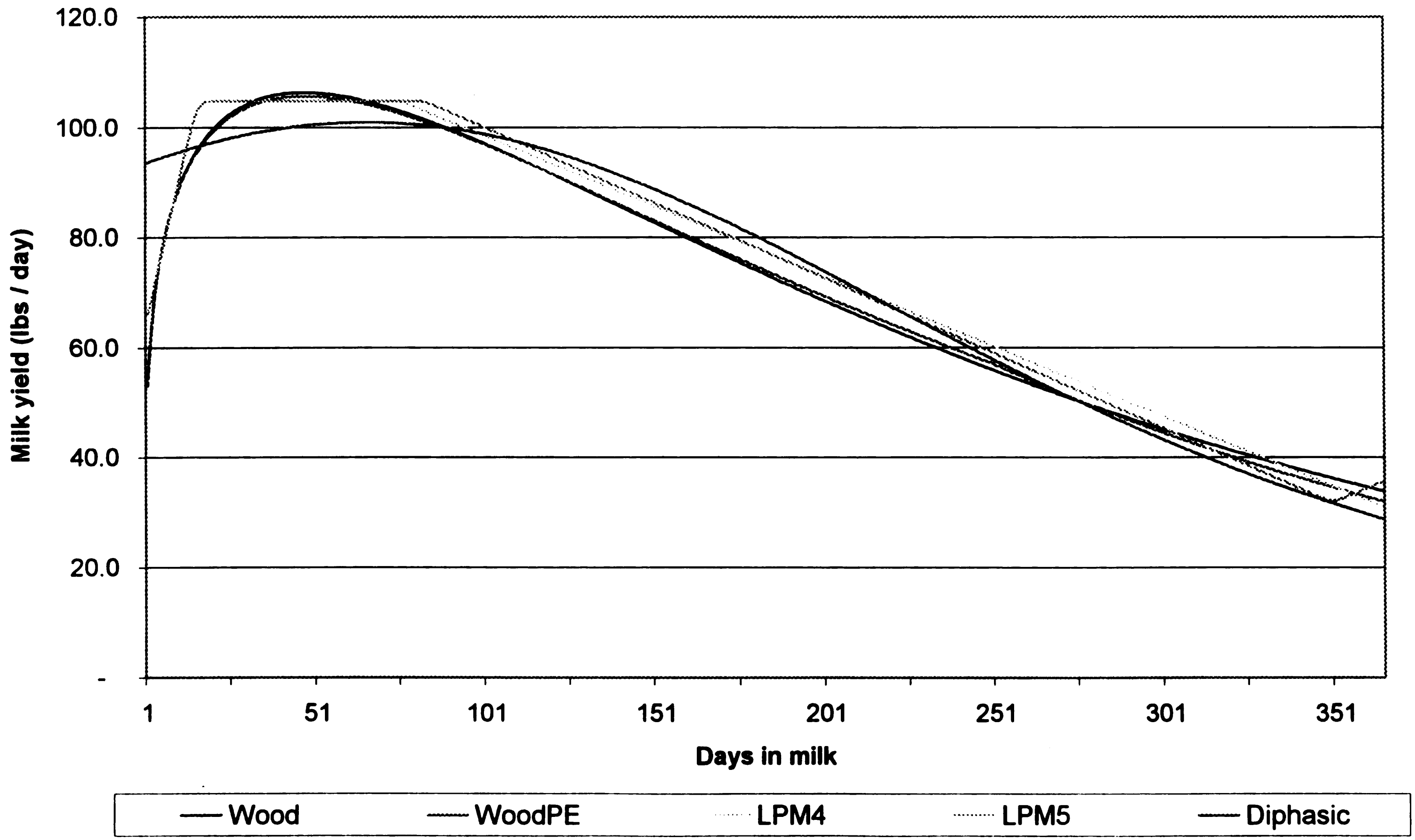


Figure 3.13. Projected lactation milk yields for cows calving in fall



Chapter 4

EFFECTS OF LACTATION CURVE MODEL SPECFICATION ON REPRODUCTIVE MANAGEMENT DECISIONS

A reproductive management decision involves determining the value of the reproductive performance improvement and the implementation costs associated with the proposed management change. A reproductive management change should be implemented only if the expected value of the new system (with the management change) exceeds that of the current system. The decision analysis model outlined in Chapter 2 provides a framework for evaluating the annualized net returns for alternative herd reproductive management change scenarios.

In this reproductive model, the cash flows for lactations of different calving intervals are first quantified and standardized to their value at the beginning of lactation using present value analysis. Then, annuity equivalent values of each of these lactations and the distribution of calving intervals and management groups are determined. The total herd values of the current herd and the alternatives is the sum of the annuity equivalent values for the herd distribution. The difference between the value of each alternative and the current herd is the expected increase (or decrease) in annualized returns to the herd at steady state herd management group proportions under the new reproductive management system.

In this chapter, four potential reproductive management change scenarios are evaluated using this framework. The goal of this analysis is to compare decision analysis results across lactation curve models used to project the change in milk yield for a case herd. Each scenario was evaluated using results from each of the empirical lactation curve models discussed in Chapter 3. Only milk yield revenues and feed expenses varied with the selected empirical lactation curve model. Although the values varied across lactation curve model, all lactation curve models yielded identical rankings for the value of the scenarios.

4.1 Farm characteristics

The financial and production characteristics of the case farm were based upon recent farm summaries and other industry data (Nott, 2000; OSU Extension 1999). Market prices and farm characteristics used in this analysis are shown in Table 4.1. The values for the case farm represent a typical mid-size (i.e., 150-400 cows) Midwest dairy. The case herd maintains 100 milking cows with constrained milking herd space but unconstrained dry cow space, as would be the case when the milking herd is housed in a freestall barn and dry cows in bedded pack or pasture.

Later in this chapter, the role of key values and characteristics are examined through sensitivity analysis. Farm financial characteristics examined in the sensitivity analysis include herd size, opportunity cost of capital, milk price, and feed costs. Farm production characteristics include herd health, labor efficiency, and nonreproductive culling rates.

4.1.1 Financial characteristics

Opportunity cost of capital

An opportunity cost of capital of 8%, equal to the farm's weighted average cost of capital, was used to derive all present value interest and annuity factors. An 8% annual opportunity cost of capital reflects an average value for a moderately leveraged Michigan dairy, consistent with Harsh et al. (2001). All reproductive management investments were considered to have the same financial risk as the farm, a standard implicit assumption in present value analysis. Since the reproductive investments are relatively small, they were assumed to have the same debt-equity mix as the farm. The investments were considered too small relative to the size of the farm to influence farm liquidity or solvency.

The opportunity cost of capital, rather than the incremental cash flows and present value of lactations, was adjusted for inflation to simplify the calculations. The discount rate used in the analysis was 5%. The average inflation value considered was 3%, which is generally consistent with expected inflation values. Milk production is commonly expected to increase 2% annually. Agricultural statistics indicate that labor wage can be expected to grow at 3.7% annually, while expected rise in other production costs is 2.5% per year (USDA, 2000).

Taxes and depreciation

The marginal tax rate on ordinary income for the case farm totals 34.9%, consisting of 28% federal tax, 4% state tax, and 2.9% Medicare tax. The farm is not subject to additional social security tax. Capital gains are taxed at 20% (IRS, 2001). Replacement heifers are depreciated using the five year modified accelerated capital recovery system (MACRS).

4.1.2 Production characteristics and market prices

Milk revenues

Milk yield revenues were based on a unit milk price of $13.50 per hundredweight. Milk yield continues until 60 days prior to the end of the calving interval, in order to allow a dry period before the next lactation, unless production falls below 20 pounds per day. In this case, milk yield was stopped and the dry period is begun early. Milk yields for each alternative were projected using each of the four lactation curve models from Chapter 3, adjusting the end of lactation and the onset of the pregnancy effect for the various calving intervals.

Calf revenues

Heifer calves are sold at weaning (eight weeks) for $250 and bulls at one week of age for $50. Calves are managed in groups by hired labor, with an average labor requirement of 20 minutes per head per week. Calf mortality rate prior to sale is 5%.

Culling revenues and replacement costs

Culling for non-reproductive reasons is 25% of each management group per year. This value affects only the change in herd distribution, not the cash flows associated with particular lactations. Cull cows are valued at $450 per head, while replacement heifers are purchased for $1,400 per head.

Feed expenses

Feed expenses were determined using a unit price of $0.06 per pound of dry matter. Feed requirements were directly related to milk yield, with a conversion rate of 0.5 pounds of dry matter per pound of additional milk.

Breeding expenses

Breeding expenses for semen and supplies total $22.00 for each breeding. A timed breeding using Ovsynch adds an additional $18 to the cost of each breeding for the hormone injections and related supplies.

Labor expenses

Hired labor is valued at $12 per hour, which would consist of all wage, benefits, and applicable taxes. The opportunity cost of labor to reproduction was assessed at $25 per hour to representing the value of the farmer's labor in alternative activities on the farm.

Herd health expenses

Herd health disorders associated with the beginning of lactation, including metabolic disorders and some types of severe mastitis, occur in 15% of cows calving. Veterinary expenses, consistinf of veterinary service fees and the costs of treatment products, associated with treatment of herd health disorders total $100 per case. Managing the care of a cow with a health disorder requires four hours of management labor per case.

4.2 Herd reproductive management: Current system and change scenarios

4.2.1 Current herd reproductive management system

Under the current herd reproductive management system, labor use for estrus detection and breeding requires a management labor input of one hour per day visually detecting estrus and one-quarter hour per breeding throughout the year. All cows meeting the minimum days to first service and detected in estrus are bred. Breeding begins at 70 days in milk for all management groups.

The level of reproductive performance (pregnancy rate) that results from this management system varies across management groups. Pregnancy rates in winter and spring months far exceed those in summer and fall months[7]. Estrus detection success is severely impaired in summer months, since cows under heat stress often fail to show signs of estrus. Since heat stress also impairs follicular development, conception rates are depressed in the months that follow. Pregnancy rates for first lactation heifers are generally higher than mature cows and less affected by season (Lucy, 2001).

Reproductive performance in a herd can be increased by improving the current visual estrus detection system and (or) by implementing a new estrus detection system. Table 4.2 compares the labor use, breeding costs, and reproductive performance in the current herd reproductive management system to that associated with each scenario. Four

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[7] It is important to note that the effects of season on reproduction express themselves in cows that calved one to two seasons earlier, since breeding occurs between 70 and 250 days in milk.

alternative reproductive management change scenarios were evaluated in this analysis – two involving additional labor to observe estrus and two that incorporate the Ovsynch hormonal synchronization protocol into the reproductive management system. The Ovsynch protocol – a series of three injections followed by timed breeding – eliminates the need for estrus detection in that estrous cycle (Pursley et al., 1997).

4.2.2 Allocating additional labor to visual estrus detection.

Additional labor for estrus detection provided by management labor can improve estrus detection rate significantly (Stevenson, 2001). In the first alternative (LBR1), an additional hour of management labor is allocated each day to estrus detection. Thus, the farm manager spends two hours each day actively observing cows for signs of estrus. The estrus detection rates in each management group are expected to improve under each scenario, since observation time is a key determinant of estrus detection success.

The second alternative (LBR2) involves substituting hired labor for all management labor in estrus detection. Under this scenario, the hired labor spends 2 hours each day observing the herd for cows in estrus. Since observer skill level is also critical to the EDR (Fogwell, 1998), the expected EDR improvement is greater for the management labor scenario (LBR1) than the hired labor scenario (LBR2). The relative differences across management groups remain because they result from physiological differences across cows. Because the breeding system is unchanged, the CR in all management groups is equal to the current system.

4.2.3 Substitution of a timed breeding protocol for visual estrus detection.

The Ovsynch protocol has been promoted as a labor saving replacement for the traditional visual detection of estrus. The Ovsynch protocol is associated with an average 40% pregnancy rate each time it is conducted, higher than most visual estrus detection systems (Pursley et al., 1997). Ovsynch pregnancy rates are affected by parity and season in the same patterns as traditional reproductive methods, although the effects are less dramatic (Tenhagen et al., 2001). For all management groups in this analysis, pregnancy rates associated with an Ovsynch breeding exceed those for breedings accomplished with traditional methods. Perfect application of the protocol was assumed for both scenarios.

Because the three-injection protocol allows timed breeding, observation of estrus is not needed. Applied to the entire herd, the herd's estrus detection system can be eliminated. The Ovsynch system can also be used to partially replace the current estrus detection system. In this analysis, both full implementation (OVS1) and a supplemental use in conjunction with a modest reduction in visual estrus detection (OVS2) were considered.

Full replacement of visual estrus detection with Ovsynch

In OVS1, the hormonal synchronization protocol is conducted on all cows in the breeding herd beginning at 70 days in milk and continuing until they are pregnant or culled. Full replacement of current reproductive management system with the Ovsynch protocol eliminates the need for estrus detection in the herd. However, nonpregnant cows are only bred on alternating estrous cycles. Without visual estrus detection, nonpregnant cows are not identified at the following estrus. Rather, they are diagnosed by palpation at 40 days after breeding (the approximate equivalent of two estrous cycles), at which time the Ovsynch protocol can be conducted again.

Partial replacement of visual estrus detection with Ovsynch

A partial replacement scenario (OVS2) that captures the increased PR of the Ovsynch system, as well as the reduced turnaround time of a visual estrus detection system, was also examined. Under the OVS2 scenario, the Ovsynch protocol is applied to all cows for their first breeding at 70 days in milk, after which cows return to the regular breeding herd. In their next cycle, cows are observed for signs of estrus and bred if detected. Thus, the first service pregnancy rate is 40%, while EDR and CR for future cycles remain at the original herd values.

Since Ovsynch is not conducted regularly on all cows, the visual estrus detection system for the herd must remain in place. However, visual estrus detection need only occur during one week of every three-week cycle. Applying the Ovsynch protocol "partially" to the entire herd results in synchronization of the estrous cycles of all cows at the first service. Nonpregnant cows continue their cycle such that subsequent estrus periods occur at approximately the same time. Like the current system, management labor conducts all estrus detection.

4.3 Results and discussion

4.3.1 Annuity equivalents by management group

Table 4.3 and 4.4 contain the annuity equivalent values for heifers and cows for each calving interval in each season of calving by lactation curve model. These values represent the annualized gross margin for the lactation of a given calving interval in the management group with constant replication -- that is, when the number of cows in each calving interval management group is continuously maintained. As a result, differences in annualized values across calving intervals, management groups, and lactation curves represent only the contribution of the group to the herd value. The value of changing the calving interval cannot be inferred without adjusting for the changes in herd structure associated with specific reproductive performance changes.

Calving interval

Within management group, annuity equivalent values were generally higher for shorter calving intervals. Values decreased at an increasing rate as calving intervals became longer. While annual differences between the shortest two calving intervals were approximately $1.00 to $1.50 for heifers and $2.00 to $2.50 for cows, the difference between the longest two calving intervals was nearer to $2.00 for heifers and $3.00 to $5.00 for cows. Cull lactations represent failure to conceive -- i.e., not pregnant after 254 days in milk. The value of these lactations was lower than other calving intervals because it reflects the cost of the resulting replacement.

Management groups

Cow lactations generated more annualized net income than heifer lactations within season of calving. This pattern held across season of calving, except that summer cow lactations were less valuable than winter heifer lactations. Lactations of heifers and cows calving in the fall winter were generally more valuable than those calving in other seasons. Summer lactations were the least valuable for both heifers and cows, likely reflecting the lasting influence of heat stress on milk yields over lactation.

Patterns across lactation curve models

The patterns in calving intervals and management groups discussed above were similar across lactation curve functional form. One notable exception was the ranking of calving intervals for spring-calving heifers by the WoodPE model, which showed the highest value for a 62 week calving interval. Differences between lactation curve models for same calving interval and management group ranged from $1.00 to $5.00 for heifers and $10.00 to $20.00 for cows. Cull lactations varied the most, caused by differences across lactation curve model in the modeling of the pregnancy effect (and its removal). The value of cull lactations of the same calving interval and management group exceeded $10 for heifers and $25 for cows.

4.3.2 Decision results by lactation curve model

The analytical results for the reproductive management change scenarios, shown in Table 4.5, indicated that decision results were consistent across all lactation curve models. The rankings of the alternatives were identical across lactation curve model, despite variation in the expected change in annualized returns of the alternative change scenarios by $50 to

$150. The full implementation of Ovsynch (OVS1) had the highest value for this herd across all lactation curve models. Using the Wood model, annualized net farm income was expected to be $1,176 higher than the current system once the OVS1 was implemented and steady state was reached. The analogous values under the LPM and diphasic models were $1,292 and $1,342, respectively.

OVS2 is associated with significant improvement in reproductive performance as well as reducing management labor use. Although increasing estrus detection by management labor (LBR2) provides a similar improvement in reproductive performance, implementing this change is expected to decrease net farm income by $330 to $600 per year, depending upon the selected lactation curve model. LBR2 increases management labor requirements. Replacing the current visual estrus detection system by hiring additional labor (LBR1) or partially with Ovsynch (OVS1) would also increase net farm income, but to a lesser degree. These scenarios captured lesser amounts of reproductive performance improvement and reduction in management labor needs.

The expected change in milk revenues made up a relatively small portion of the total expected change associated with these scenarios. In Table 4.6, the expected change in annualized returns for each of the change scenarios is partitioned into four categories – milk revenue over feed costs (IOFC), change in labor costs, change in the net cost of replacement, and all other cash flow changes. Of these, only the IOFC category was affected by the lactation curve model selection.

IOFC values for the nonlinear models were closer to each other than either of the Wood models. Values from the Wood models were lower than the nonlinear models. Differences in IOFC between across lactation curve models were large relative to IOFC values but did not affect the decision. The Wood models predicted a slight decrease in IOFC while the nonlinear models predicted increases for the labor scenarios. The Wood PE model also predicted a decrease in IOFC for the Ovsynch scenarios. The increase projected by the basic Wood model was only a fraction of the projection by both nonlinear models. Since the annuity equivalent values in the Wood model decreased progressively with increasing calving intervals, these sign differences are not related to the Wood model's ability to predict lactation extension. Rather, differences from the nonlinear models result from differences in characterizing lactation curve shape across management groups. The shift in herd structure toward management groups with lower annualized values caused larger decreases in value by the Wood model than the nonlinear models.

Differences across IOFC projections by lactation curve model were generally small relative to other components of the scenario values. A large portion of the change scenario's value results from the change in labor costs. Whereas savings in labor costs were $1,056 and $697 for OVS1 and OVS2, respectively, the largest estimated changes in IOFC (diphasic model) were $175 for OVS1 and $103 for OVS2. Changes in replacement and other cash flows, too, often exceeded the expected change in the IOFC for all lactation curve models.

4.3.3 Sensitivity analysis

In order to examine the influence of key assumptions on the in results across the lactation curve models, the analysis was run at high and low expected values for the market prices and farm characteristics. Farm financial characteristics included herd size, opportunity cost of capital, milk price, and feed costs. Farm production characteristics included herd health, labor efficiency, and nonreproductive culling rates. Additionally, unit costs for labor change scenarios and labor use for Ovsynch were examined. The values used in the sensitivity analysis are summarized in Table 4.7.

Results for each of these analyses are shown in Tables 4.8 through 4.11. Despite the differences in projected scenario values across lactation curve models, scenario rankings were identical for all characteristics. OVS1 resulted in the largest increase in annualized returns, followed by OVS2 and LBR2. Most analyses indicated that LBR1 would result in decreased annualized returns.

The Wood models consistently reported lower values for each alternative than the nonlinear (LPM4 and diphasic) models. Since each alternatives increased the proportion of the herd with shorter calving intervals, this finding is consistent with previous findings that the Wood model overestimates late lactation yields (Vargas et al., 2000). The effect was much more pronounced for cows than for heifers. As such, the Wood models provided more conservative estimates of the value of reproductive performance improvements.

The value of incorporating a pregnancy effect into the Wood model, as in WoodPE, is questionable. The WoodPE model did not always lead to analytical results closer to the more accurate nonlinear models. Replacing the days pregnant variable (DP_t) with an adjusted days pregnant variable ($AdjDP_t$), used with the diphasic model, may enhance the model's ability to capture the milk yield depression associated with late gestation.

4.4 Summary and conclusions

Four alternative reproductive management scenarios to improve reproductive performance were evaluated using the reproductive decision analysis model developed in Chapter 2. Analysis was conducted using milk yield projections from each of the lactation curve models examined in Chapter 3. Two alternatives involved allocating additional labor – hired or management – to improve estrus detection rates. The other two substituted partially or fully the Ovsynch timed breeding protocol for estrus detection. The case farm was designed to be representative of mid-size Midwest dairies.

Differences in annuity equivalent values for calving intervals within each management group were consistent with previous findings. In general, annuity equivalents for shorter calving intervals were more valuable than longer calving intervals. However, annuity equivalents for cow lactations were higher than heifers, and winter and fall calving lactations were greater than those calving in spring and summer. Thus, management changes that result in a relative increase in cow and (or) winter lactations will have a higher value than those that shift toward heifer and (or) summer lactations. Results indicated that the full implementation of the Ovsynch protocol had the highest value for the case farm under a range of market prices and farm characteristics for all lactation curves.

Lactation curve models consistently agreed on value rankings for annuity equivalents and management decisions in this analysis, despite the differences in lactation curve shape and milk yield predictions found in Chapter 3. Values projected using the Wood models were lower than those from the nonlinear models. Thus, the Wood models may provide a more conservative estimate of the change in milk revenues and feed costs resulting from a change in reproductive performance. Nonlinear models may provide more accurate results, since they show better fit throughout lactation. However, other factors affecting the projected value of reproductive management changes may be more important. Changes in labor and replacement costs were generally larger than the changes in milk revenues over feed costs. As a result, use of the nonlinear models for farm-level management decision analysis may not be worth the effort.

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Table 4.1. Farm data used in reproductive management decision analysis.

Price data		
Replacement cost	$1,400.00	per head
Cull price	$450.00	per head
Calf value		
Heifer (at weaning)	$250.00	per head
Bull (at 1 week)	$75.00	per head
Milk price	$13.50	per CWT
Feed cost	$0.06	per lb DM
Dry cow cost	$2.00	per day
Veterinary expense	$100.00	per case
Breeding expense	$22.00	per breeding
Hired labor wage	$12.00	per hour
Opportunity cost of management labor	$25.00	per hour
Opportunity cost of capital	8.00%	per year
Inflation	3.00%	per year
Marginal tax rate	35%	
Capital gains tax rate	20%	

Labor use data		
Labor hours per calf (average)	1.5 hrs	Hired
Labor hours per health disorder case	4 hrs	MGT
Labor hours per breeding	0.5 hrs	MGT

Other herd characteristics		
Milking herd size	100	head
Health disorder incidence[1]	15%	
Milk yield for early dry off	20	lbs

[1] Percent of cows that suffer from mastitis or metabolic disorders in a given lactation. Each afflicted cow is also referred to as a case.

Table 4.2. Comparison of price and herd characteristics across reproductive management change scenarios.

	Current System		LBR1 Hired Labor		LBR2 Mgmt Labor		OVS1 Partial Ovsynch				OVS2 Full Ovsynch	
							First breeding		Thereafter [1 wk / period]		Alternating Cycles	
Hrs ED / day:												
Hired	0		2		0		0		0		0	
Mgmt	1		0		2		0		1		0	
Hrs / brdg	0.25		0.25		0.25		0.35		0.25		0.35	
Breeding cost	$ 22.00		$ 22.00		$ 22.00		$ 40.00		$ 22.00		$ 40.00	
Days to first service	70 days		70 days		70 days		70 days				70 days	
Reproductive performance:	EDR	CR	EDR	CR	EDR	CR	EDR	CR	EDR	CR	EDR	CR
Heifer, Winter	50%	50%	65%	50%	80%	50%	100%	40%	50%	50%	100%	40%
Heifer, Spring	30%	30%	45%	30%	60%	30%	100%	30%	30%	30%	100%	30%
Heifer, Summer	40%	30%	55%	30%	70%	30%	100%	30%	40%	30%	100%	30%
Heifer, Fall	50%	50%	65%	50%	80%	50%	100%	40%	50%	50%	100%	40%
Cow, Winter	50%	40%	65%	40%	60%	40%	100%	35%	50%	40%	100%	35%
Cow, Spring	30%	20%	45%	20%	70%	20%	100%	25%	30%	20%	100%	25%
Cow, Summer	40%	20%	55%	20%	80%	20%	100%	25%	40%	20%	100%	25%
Cow, Fall	50%	40%	45%	40%	70%	40%	100%	35%	50%	40%	100%	35%

[1] Increased breeding costs for Ovsynch alternatives reflect the cost of injections and other supplies, in addition to semen and supplies, needed for each breeding.

[2] Estrus detection and conception rates for "Full Ovsynch" are only applicable to alternating estrous cycles.

Table 4.3. Annuity equivalent values for heifer lactations by calving interval and season of calving.

LINEAR (WOOD) MODELS.

Calving	Wood				WoodPE			
interval	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall
50 wks	$ 126.32	$ 115.97	$ 114.01	$ 114.43	$ 123.78	$ 110.97	$ 109.63	$ 115.49
53 wks	$ 124.77	$ 114.79	$ 112.94	$ 113.28	$ 122.68	$ 111.72	$ 109.28	$ 115.29
56 wks	$ 123.13	$ 113.48	$ 111.71	$ 111.98	$ 121.45	$ 112.24	$ 108.74	$ 114.88
59 wks	$ 121.33	$ 112.00	$ 110.29	$ 110.49	$ 120.02	$ 112.49	$ 107.97	$ 114.21
62 wks	$ 119.56	$ 110.52	$ 108.85	$ 108.99	$ 118.60	$ 112.64	$ 107.15	$ 113.46
65 wks	$ 117.74	$ 108.98	$ 107.33	$ 107.42	$ 117.12	$ 112.64	$ 106.21	$ 112.59
68 wks	$ 115.90	$ 107.39	$ 105.76	$ 105.80	$ 115.57	$ 112.51	$ 105.17	$ 111.61
71 wks	$ 114.03	$ 105.78	$ 104.14	$ 104.14	$ 113.99	$ 112.27	$ 104.06	$ 110.54
74 wks	$ 112.09	$ 104.08	$ 102.44	$ 102.40	$ 112.31	$ 111.86	$ 102.83	$ 109.33
77 wks	$ 110.21	$ 102.42	$ 100.77	$ 100.70	$ 110.68	$ 111.42	$ 101.61	$ 108.13
CULL	$ 87.81	$ 81.71	$ 79.76	$ 79.96	$ 90.97	$ 92.44	$ 71.59	$ 87.74

NONLINEAR MODELS.

Calving	LPM 4				Diphasic			
interval	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall
50 wks	$ 131.71	$ 120.39	$ 117.94	$ 121.05	$ 128.76	$ 121.58	$ 118.83	$ 122.62
53 wks	$ 130.29	$ 119.39	$ 117.02	$ 120.43	$ 127.53	$ 127.96	$ 117.83	$ 121.40
56 wks	$ 128.78	$ 118.26	$ 115.95	$ 119.66	$ 126.18	$ 127.00	$ 116.56	$ 119.96
59 wks	$ 127.11	$ 116.95	$ 114.67	$ 118.69	$ 124.59	$ 125.76	$ 114.97	$ 118.28
62 wks	$ 125.48	$ 115.63	$ 113.38	$ 117.71	$ 122.90	$ 124.38	$ 113.28	$ 116.60
65 wks	$ 123.79	$ 114.23	$ 111.98	$ 116.64	$ 120.98	$ 122.75	$ 111.46	$ 114.86
68 wks	$ 122.06	$ 112.76	$ 110.51	$ 115.50	$ 118.81	$ 120.84	$ 109.55	$ 113.11
71 wks	$ 120.29	$ 111.24	$ 108.96	$ 114.29	$ 116.37	$ 118.63	$ 107.60	$ 111.37
74 wks	$ 118.42	$ 109.60	$ 107.30	$ 112.96	$ 113.57	$ 116.05	$ 105.58	$ 109.60
77 wks	$ 116.59	$ 107.98	$ 105.64	$ 111.64	$ 110.53	$ 113.21	$ 103.63	$ 107.95
CULL	$ 96.19	$ 83.37	$ 76.02	$ 90.15	$ 93.28	$ 77.90	$ 74.65	$ 78.84

Table 4.4. Annuity equivalent values for cow lactations by calving interval and season of calving.

LINEAR (WOOD) MODELS.

Calving	Wood				WoodPE			
interval	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall
50 wks	$ 141.72	$ 134.35	$ 124.51	$ 140.11	$ 139.43	$ 128.68	$ 119.51	$ 139.06
53 wks	$ 138.52	$ 131.46	$ 121.62	$ 136.79	$ 137.48	$ 127.16	$ 118.24	$ 136.24
56 wks	$ 135.25	$ 128.50	$ 118.67	$ 133.40	$ 135.33	$ 125.42	$ 116.74	$ 133.29
59 wks	$ 131.86	$ 125.40	$ 115.63	$ 129.90	$ 132.93	$ 123.42	$ 114.98	$ 130.18
62 wks	$ 128.57	$ 122.40	$ 112.68	$ 126.51	$ 130.52	$ 121.38	$ 113.18	$ 127.13
65 wks	$ 125.32	$ 119.41	$ 109.76	$ 123.16	$ 128.03	$ 119.25	$ 111.27	$ 124.07
68 wks	$ 122.10	$ 116.44	$ 106.88	$ 119.86	$ 125.49	$ 117.06	$ 109.29	$ 121.03
71 wks	$ 118.95	$ 113.53	$ 104.05	$ 116.63	$ 122.93	$ 114.82	$ 107.26	$ 118.02
74 wks	$ 115.79	$ 110.60	$ 101.23	$ 113.41	$ 120.29	$ 112.50	$ 105.14	$ 114.99
77 wks	$ 112.78	$ 107.80	$ 97.32	$ 109.90	$ 117.73	$ 110.23	$ 102.26	$ 111.86
CULL	$ 103.79	$ 96.48	$ 85.24	$ 101.49	$ 97.11	$ 84.82	$ 71.92	$ 84.37

NONLINEAR MODELS.

Calving	LPM 4				Diphasic			
interval	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall
50 wks	$ 136.16	$ 139.71	$ 131.51	$ 148.64	$ 147.81	$ 143.07	$ 137.27	$ 148.09
53 wks	$ 133.25	$ 136.90	$ 130.09	$ 145.17	$ 145.02	$ 139.94	$ 133.97	$ 144.15
56 wks	$ 130.18	$ 133.91	$ 128.44	$ 141.48	$ 142.40	$ 136.68	$ 130.70	$ 140.08
59 wks	$ 126.90	$ 130.67	$ 126.50	$ 137.51	$ 139.90	$ 133.26	$ 127.43	$ 135.84
62 wks	$ 123.60	$ 127.40	$ 124.49	$ 133.50	$ 137.73	$ 129.95	$ 124.39	$ 131.71
65 wks	$ 120.22	$ 124.02	$ 122.07	$ 129.35	$ 135.79	$ 126.67	$ 121.48	$ 127.62
68 wks	$ 116.75	$ 119.90	$ 118.92	$ 124.16	$ 134.07	$ 123.46	$ 118.71	$ 123.62
71 wks	$ 112.66	$ 115.49	$ 115.84	$ 118.64	$ 132.57	$ 120.34	$ 116.11	$ 118.48
74 wks	$ 107.60	$ 111.26	$ 112.83	$ 113.49	$ 131.19	$ 117.26	$ 113.58	$ 113.30
77 wks	$ 103.08	$ 107.30	$ 110.01	$ 108.81	$ 130.08	$ 114.36	$ 111.27	$ 108.52
CULL	$ 78.02	$ 75.93	$ 102.17	$ 93.10	$ 113.52	$ 87.47	$ 75.84	$ 88.28

Table 4.5. Comparison of the expected change in annualized net income for four alternative reproductive managment scenarios.

		LBR1 Mgmt		LBR2 Hired		OVS1 Partial		OVS2 Full
Total:								
Wood	$	(578.30)	$	166.82	$	855.19	$	1,175.65
WoodPE	$	(591.44)	$	132.19	$	775.70	$	1,119.21
LPM4	$	(451.65)	$	217.71	$	904.98	$	1,291.62
Diphasic	$	(330.37)	$	267.97	$	909.52	$	1,342.15
Per Cow (average):								
Wood	$	(5.78)	$	1.67	$	8.55	$	11.76
WoodPE	$	(5.91)	$	1.32	$	7.76	$	11.19
LPM4	$	(4.52)	$	2.18	$	9.05	$	12.92
Diphasic	$	(3.30)	$	2.68	$	9.10	$	13.42

Table 4.6. Components of the expected change in annualized net income for four alternative reproductive managment scenarios: Labor, replacement, IOFC, and other cash flows .

		LBR1 Mgmt		LBR2 Hired		OVS1 Partial		OVS2 Full
Change in cash flows								
Labor	$	(1,141.84)	$	5.64	$	696.97	$	1,056.15
Replacement	$	(303.62)	$	(262.49)	$	(174.33)	$	(501.92)
Other	$	878.18	$	456.27	$	283.54	$	613.38
Change in milk income over feed costs								
Wood	$	(11.03)	$	(32.60)	$	49.01	$	8.03
WoodPE	$	(24.17)	$	(67.23)	$	(30.48)	$	(48.41)
LPM4	$	115.63	$	18.29	$	98.80	$	124.00
Diphasic	$	236.91	$	68.55	$	103.33	$	174.53

Table 4.7. Data used in sensitivity analysis for reproductive management decisions.

Scenario characteristics	**Case**	**Low**	**High**	
Relative cost of scenarios [Labor:Capital]				
Hired labor	$ 12.00	$ 8.00	$ 18.00	per hour
Management labor	$ 25.00	$ 15.00	$ 50.00	per hour
Ovsynch injections	$ 18.00	$ 24.00	$ 12.00	per breeding
Ovsynch labor use	0.35	0.10	0.50	hrs per brdg

Farm financial characteristics	**Case**	**Low**	**High**	
Milk vs. feed prices				
Milk price	$13.50	$11.00	$16.00	per CWT
Feed cost	$0.06	$0.08	$0.04	per lb DM
Opportunity cost of capital	8%	6%	10%	

Farm production characteristics	**Case**	**Low**	**High**	
Culling rates (non-reproductive)	25%	15%	40%	
Herd health costs				
Health disorder incidence[1]	15%	7%	30%	
Veterinary expense	$ 100.00	$ 50.00	$ 200.00	per case
Labor efficiency				
Labor hrs per fresh cow	1.50	2.00	1.00	hrs hired
Labor hrs per health disorder case	4.00	6.00	2.00	hrs mgmt
Labor hrs per breeding	0.25	0.50	0.10	hrs mgmt
Milking herd size	100	50	150	milking cows

[1] Percent of cows that suffer from mastitis or metabolic disorders in a given lactation. Each afflicted cow is also referred to as a case.

Table 4.8. Comparison of the expected chagen in annualized net farm income with various scenario characteristics.

RELATIVE SCENARIO COST [Labor:Ovsynch]

	LOW				HIGH			
	LBR1 Mgmt	**LBR2 Hired**	**OVS1 Partial**	**OVS2 Full**	**LBR1 Mgmt**	**LBR2 Hired**	**OVS1 Partial**	**OVS2 Full**
Wood	$ (121.59)	$ 93.93	$ 518.70	$ 630.55	$(1,719.99)	$ 702.18	$ 1,610.55	$ 2,354.73
WoodPE	$ (134.73)	$ 59.30	$ 439.21	$ 574.12	$(1,733.13)	$ 667.55	$ 1,531.05	$ 2,298.29
LPM	$ 5.07	$ 144.82	$ 568.49	$ 746.52	$(1,593.33)	$ 753.08	$ 1,660.34	$ 2,470.70
Diphasic	$ 126.35	$ 195.08	$ 573.03	$ 797.05	$(1,472.05)	$ 803.34	$ 1,664.87	$ 2,521.22

OVSYNCH LABOR USE

	LOW				HIGH			
	LBR1 Mgmt	**LBR2 Hired**	**OVS1 Partial**	**OVS2 Full**	**LBR1 Mgmt**	**LBR2 Hired**	**OVS1 Partial**	**OVS2 Full**
Wood	$ (578.30)	$ 166.82	$ 917.59	$ 1,258.65	$ (578.30)	$ 166.82	$ 808.40	$ 1,125.85
WoodPE	$ (591.44)	$ 132.19	$ 838.09	$ 1,202.21	$ (591.44)	$ 132.19	$ 728.90	$ 1,069.41
LPM	$ (451.65)	$ 217.71	$ 967.38	$ 1,374.62	$ (451.65)	$ 217.71	$ 858.19	$ 1,241.82
Diphasic	$ (330.37)	$ 267.97	$ 971.91	$ 1,425.15	$ (330.37)	$ 267.97	$ 862.72	$ 1,292.35

Table 4.9. Comparison of the expected change in annualized net farm income with various farm financial characteristics.

MILK AND FEED PRICES [Milk:Feed]

	LOW				HIGH			
	LBR1 Mgmt	LBR2 Hired	OVS1 Partial	OVS2 Full	LBR1 Mgmt	LBR2 Hired	OVS1 Partial	OVS2 Full
Wood	$ (574.63)	$ 177.68	$ 838.86	$ 1,172.97	$ (581.98)	$ 155.95	$ 871.53	$ 1,178.32
WoodPE	$ (583.39)	$ 154.60	$ 785.86	$ 1,135.35	$ (599.50)	$ 109.77	$ 765.54	$ 1,103.07
LPM	$ (490.19)	$ 211.61	$ 872.05	$ 1,250.28	$ (413.10)	$ 223.80	$ 937.91	$ 1,332.95
Diphasic	$ (409.34)	$ 245.12	$ 875.07	$ 1,283.97	$ (251.40)	$ 290.82	$ 943.96	$ 1,400.32

OPPORTUNITY COST OF CAPITAL

	LOW				HIGH			
	LBR1 Mgmt	LBR2 Hired	OVS1 Partial	OVS2 Full	LBR1 Hired	LBR2 Mgmt	OVS1 Partial	OVS2 Full
Wood	$ (615.55)	$ 150.44	$ 849.74	$ 1,159.83	$ 181.22	$ (544.94)	$ 859.47	$ 1,188.88
WoodPE	$ (628.45)	$ 115.66	$ 770.17	$ 1,103.36	$ 146.74	$ (558.31)	$ 780.05	$ 1,132.48
LPM	$ (487.93)	$ 201.66	$ 899.85	$ 1,276.47	$ 231.79	$ (419.24)	$ 908.93	$ 1,304.19
Diphasic	$ (365.85)	$ 252.22	$ 904.60	$ 1,327.65	$ 281.75	$ (298.75)	$ 913.26	$ 1,354.07

Table 4.10. Comparison of the expected change in annualized net farm income with various farm production characteristics.

NON-REPRODUCTIVE CULLING RATES

	LOW				HIGH			
	LBR1 Mgmt	LBR2 Hired	OVS1 Partial	OVS2 Full	LBR1 Mgmt	LBR2 Hired	OVS1 Partial	OVS2 Full
Wood	$(1,159.73)	$ 115.29	$ 825.75	$ 1,159.09	$ (644.37)	$ 138.56	$ 793.79	$ 1,095.82
WoodPE	$(1,189.26)	$ 85.76	$ 749.13	$ 1,110.04	$ (680.42)	$ 95.91	$ 709.70	$ 1,027.57
LPM	$(1,106.08)	$ 168.95	$ 880.40	$ 1,280.61	$ (531.88)	$ 185.65	$ 835.95	$ 1,202.27
Diphasic	$(1,059.35)	$ 215.68	$ 885.59	$ 1,336.46	$ (414.54)	$ 240.66	$ 839.63	$ 1,245.70

HERD HEALTH COSTS

	LOW				HIGH			
	LBR1 Mgmt	LBR2 Hired	OVS1 Partial	OVS2 Full	LBR1 Mgmt	LBR2 Hired	OVS1 Partial	OVS2 Full
Wood	$ (579.83)	$ 166.86	$ 847.33	$ 1,172.22	$ (580.21)	$ 166.88	$ 845.37	$ 1,171.36
WoodPE	$ (592.97)	$ 132.23	$ 767.84	$ 1,115.78	$ (593.35)	$ 132.25	$ 765.87	$ 1,114.93
LPM	$ (453.17)	$ 217.76	$ 897.12	$ 1,288.19	$ (453.55)	$ 217.77	$ 895.15	$ 1,287.33
Diphasic	$ (331.89)	$ 268.02	$ 901.66	$ 1,338.72	$ (332.27)	$ 268.03	$ 899.69	$ 1,337.86

LABOR EFFICIENCY

	LOW				HIGH			
	LBR1 Mgmt	LBR2 Hired	OVS1 Partial	OVS2 Full	LBR1 Mgmt	LBR2 Hired	OVS1 Partial	OVS2 Full
Wood	$ (555.59)	$ 189.93	$ 814.01	$ 1,133.91	$ (728.48)	$ 15.84	$ 812.04	$ 1,133.05
WoodPE	$ (568.73)	$ 155.30	$ 734.51	$ 1,077.47	$ (741.62)	$ (18.79)	$ 732.55	$ 1,076.61
LPM	$ (428.93)	$ 240.82	$ 863.79	$ 1,249.88	$ (601.83)	$ 66.74	$ 861.83	$ 1,249.02
Diphasic	$ (307.65)	$ 291.08	$ 868.33	$ 1,300.41	$ (480.55)	$ 117.00	$ 866.36	$ 1,299.55

Table 4.11. Comparison of the expected change in annualized net farm income at various milking herd sizes.

MILKING HERD SIZE	LOW				HIGH			
	LBR1 Mgmt	LBR2 Hired	OVS1 Partial	OVS2 Full	LBR1 Mgmt	LBR2 Hired	OVS1 Partial	OVS2 Full
Wood	$ (840.96)	$ 105.48	$ 797.31	$ 1,139.63	$ (315.65)	$ 228.15	$ 913.08	$ 1,211.66
WoodPE	$ (847.53)	$ 88.17	$ 757.56	$ 1,111.41	$ (335.36)	$ 176.21	$ 793.84	$ 1,127.01
LPM	$ (777.63)	$ 130.93	$ 822.20	$ 1,197.61	$ (125.67)	$ 304.49	$ 987.76	$ 1,385.62
Diphasic	$ (716.99)	$ 156.06	$ 824.47	$ 1,222.88	$ 56.26	$ 379.88	$ 994.56	$ 1,461.41

Chapter 5

SUMMARY AND CONCLUSIONS

5.1 Summary of methods and results

An economic simulation model was developed to evaluate reproductive management decisions for a dairy farm. Reproductive management was considered as an investment, with changes in the reproductive management system altering the capital investment and return structure for the herd. The model considers calving intervals on the basis of annualized net returns to the dairy herd enterprise – first calculating the present value of each lactation, then converting it to an annuity equivalent. The model implicitly deals with management labor and capital constraints of dairy farms by including the related opportunity costs. As well, the model considers the changes in herd structure associated with reproductive performance improvements.

In order to evaluate the influence of lactation curve specification, the reproductive analysis was run using milk yield projections from for common lactation curve specifications – two variations on the Wood model, a modified LPM model, and the diphasic model. Each lactation curve was fitted to 362 lactations of daily milk yield data from a dairy herd (over three years). The lactations were pooled into eight management groups defined by parity and season of calving. Differences in lactation curve shape were evident across management groups, suggesting differential values for improving reproductive performance. First lactation heifers, as well as all cows calving in summer, showed lower but more persistent peak yields than their mature and (or) winter-calving counterparts.

Analysis of the residuals of the lactation curve models across stage of lactation and management group indicated that the fit of the nonlinear models (LPM and diphasic models) is consistently better than the Wood models. Nonlinear models showed consistently higher R^2 and lower root mean square error (RMSE) than the Wood models for most stages of lactation in all management groups. The Wood results were similar to the nonlinear models for heifer lactations but relatively poor (lower R^2 and higher RMSE) for cow lactations.

Annuity equivalents for lactations of each calving interval and management group differed across lactation curve models. Similar to results in previous studies, shorter calving intervals had higher annuity equivalents than longer calving intervals. In general, heifer lactations were lower in value than mature cow lactations, and winter lactations were more valuable than spring and summer lactations. It is important to note that these lactations must be considered in the context of the herd decision. Changes to the reproductive performance of individual management groups affect the distribution of management groups in the herd. The nonlinear models showed greater differences in value across calving intervals and management groups.

Incorporated into the reproductive model, however, all lactation curve models agreed on the rankings of the management change scenarios. The net scenario values assessed using the Wood models were consistently lower than both the nonlinear models. No consistent pattern in values was found between the Wood models with and without the pregnancy modification. Changes in labor and replacement costs associated with each investment scenario were larger than the changes in milk income over feed costs for all lactation curve models.

5.2 Conclusions: Selecting an empirical lactation curve model

Lactation curve specification influences the annuity equivalent values, the weighted sum of which compose the herd value. Changes in herd structure from a reproductive management change affect the distributions of both management groups and calving interval. The lactation curve functional form must capture differences in lactation curve shape across both management groups as well as calving intervals. However, changes in labor and replacement costs were consistently larger than the changes in milk income over feed costs. Thus, accurate projections of all three components are critical to accurate reproductive management analysis.

The simple mathematical form of the Wood model did not compromise the reproductive decision results in this analysis despite its inability to reflect all lactation curve shape differences across management groups. The rankings of alternative management change scenarios were identical to nonlinear lactation curve models in all analyses. The Wood model consistently provided the most conservative estimate of the impact of each proposed reproductive management change. The greatest improvement in accuracy of milk yield projection would likely be gained by using one of the nonlinear models for cow lactations. Cow lactations are more likely to violate the standard Wood shape, declining at an increasing rate.

The benefit of incorporating the pregnancy effect into the Wood model was not borne out by this data. Although analysis of the milk yield regression results indicated that the model with the pregnancy effect (WoodPE) had somewhat better fit, results of the reproductive analysis were not always closer to the nonlinear models. Thus, the added estimation requirements may not be justified. Additional study may indicate a more accurate linear method of incorporating a pregnancy effect into the Wood model.

Additional study is also needed to determine the applicability of these lactation curve models to herds using bST. The additive modification proposed by Wiegel (1992) can be easily incorporated into the diphasic model, although farm-level analysis would then require nonlinear regression methods. It is also possible that the Wood model may fit bST-enhanced cow lactations more appropriately, given the slower rate of decline in these lactations.

5.3 Avenues for further research of reproductive decisions

This reproductive model provides a more rigorous economic analysis of the value of herd investments that improve reproductive performance. However, the analysis in this thesis represents four reproductive management alternatives for a single herd. Augmentation of the model may improve its usefulness. Additional scenario alternatives, as well as a range of culling assumptions, could be incorporated into the empirical model. Although such changes may require structural adjustment of the analytical model, the foundation is provided in the conceptual model.

The reproductive management decision model currently reflects whole-farm capital and management labor constraints by incorporating opportunity costs of scarce resources. Linear programming could be utilized to apply the model to farms with explicit resource constraints to the dairy herd. Alternative scenarios would be considered as individual activities with the model projecting periodic resource use for each.

Incorporating the adjustment period values into the analysis would improve the accuracy of the value projections. The model compares the value of current herd performance to the alternative scenario's value once the herd reaches steady state. Steady state is reached when management group sizes become stable after the indefinite adjustment period following a comprehensive reproductive change. Projecting management group and calving interval distributions in each period during adjustment would allow the associated annuity equivalents to be more accurately distributed, allowing the opportunity cost of capital over time to be accounted.

Dairy science research continues to develop technologies that can improve reproductive performance, providing herd managers with an increasing array of available management alternatives. In response, managers must make a large set of associated implementation decisions. Because of the inherent difficulties in projecting the effects of reproductive management changes, decision models such as the one outlined here are critical for assisting managers in making these decisions. Future research must continue to develop a simple yet sound analytical framework for analyzing increasingly diverse set of herd reproductive management decisions.

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