Economic performance of lactating dairy cows submitted for first service timed artificial insemination after a voluntary waiting period of 60 or 88 days

M. L. Stangaferro,* R. Wijma,* M. Masello,* Mark J. Thomas,† and J. O. Giordano*¹

*Department of Animal Science, Cornell University, Ithaca, NY 14853

†Dairy Health and Management Services, Lowville, NY 13367

ABSTRACT

The objective of this study was to evaluate the economic performance of dairy cows managed with a voluntary waiting period (VWP) of 60 or 88 d. A secondary objective was estimating variation in cash flow under different input pricing scenarios through stochastic Monte Carlo simulations. Lactating Holstein cows from 3 commercial farms were blocked by parity group and total milk yield in their previous lactation and then randomly assigned to a VWP of 60 (VWP60; $n = 1,352$) or 88 d (VWP88; $n = 1,359$). All cows received timed-artificial insemination (TAI) for first service after synchronization of ovulation with the Double-Ovsynch protocol. For second and greater services, cows received artificial insemination (AI) after detection of estrus or the Ovsynch protocol initiated 32 ± 3 d after AI. Two analyses were performed: (1) cash flow per cow for the calving interval of the experimental lactation and (2) cash flow per slot occupied by each cow enrolled in the experiment for an 18-mo period after calving in the experimental lactation. Extending the VWP from 60 to 88 d delayed time to pregnancy during lactation (~ 20 d) and increased the risk of leaving the herd for multiparous cows (hazard ratio = 1.21). As a result, a smaller proportion of multiparous cows calved again and had a subsequent lactation (-6%). The shift in time to pregnancy combined with the herd exit dynamics resulted in longer lactation length for primiparous (22 d) but not multiparous cows. Longer lactations led to greater milk income over feed cost and a tendency for greater cash flow during the experimental lactation for primiparous but not multiparous cows in the VWP88 group. On the other hand, profitability per slot for the 18-mo period was numerically greater (\$68 slot/18 mo) for primiparous cows but numerically reduced ($-\$85$ slot/18 mo) for multiparous cows in the VWP88 treatment. For primiparous cows most of the

difference in cash flow was explained by replacement cost, whereas for multiparous cows it was mostly explained by differences in replacement cost and income over feed cost. Under variable input pricing conditions generated through stochastic simulations, the longer VWP treatment always increased cash flow per 18 mo for primiparous and reduced cash flow for multiparous cows. In conclusion, extending the duration of the VWP from 60 to 88 d numerically increased profitability of primiparous cows and reduced profitability of multiparous cows. Such an effect depended mostly on the herd replacement dynamics and milk production efficiency.

Key words: voluntary waiting period, profitability, dairy cow, timed AI

INTRODUCTION

Achieving pregnancy for lactating dairy cows at a range of DIM that optimizes profitability for most cows depends upon the duration of the voluntary waiting period (VWP) and reducing the number and variation of days to conception after cows become eligible for pregnancy. Through the implementation of reproductive management programs and technologies that better control AI submission rates and substantially increase pregnancies per AI (P/AI) for first and subsequent AI services (Stevenson and Britt, 2017), it is possible to attain a pregnancy risk after the end of VWP that drastically reduces time to pregnancy. Thus, coupling an effective management program with a duration of the VWP that optimizes time to pregnancy during lactation may be a feasible strategy to increase dairy herd profitability.

In spite of the relevance of the VWP duration on timing of pregnancy and dairy cow profitability, limited data are available about the effect of manipulating the duration of the VWP on dairy herd performance. In addition, data available from the few experiments conducted have been inconsistent. For instance, Arbel et al. (2001), using only high-producing cows under Israeli conditions, reported an economic advantage after extending the VWP from 90 to 150 DIM for

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¹Corresponding author: jog25@cornell.edu

primiparous and from 60 to 120 DIM for multiparous cows. Conversely, Gobikrushanth et al. (2014), using a combination of retrospective data analysis and simulation, reported that extending the duration of VWP from 60 (range = 57–63 DIM) to 83 DIM (range = 64 to 121 DIM) during summer in Florida did not affect cow profitability during the experimental lactation, the subsequent lactation, or during a period of 6 yr. Furthermore, a simulation study conducted to represent dairy farms under conditions of milk production quota in the Netherlands suggested that a VWP of 6 wk was optimal and that economic losses increased gradually after extending the VWP beyond 6 wk (Inchaisri et al., 2011). These inconsistent results may be explained by differences in study design (e.g., simulation, observational study, or randomized-control experiment), inclusion criteria (e.g., only high-yielding cows that did not calve during summer, only cows that calved during summer), or other study-specific conditions (e.g., farm location, quota systems). Collectively, the lack of sufficient experimental data or variation in experimental design and results from previous research do not allow decisive conclusions about the effect of the duration of the VWP on dairy herd profitability.

Thus, the primary objective of our experiment was to compare cash flow for dairy cows managed with a VWP of 60 or 88 d. Productive performance, reproductive performance, and herd exit dynamics data from an experiment that compared a VWP of 60 or 88 d (Stangaferro et al., 2018) were used for our study. We evaluated individual cow cash flow during the calving interval in which the VWP was extended and for a fixed period of time (18 mo) after calving in the experimental calving interval. A secondary objective was estimating variation in cash flow under different input pricing scenarios through stochastic Monte Carlo simulation.

MATERIALS AND METHODS

Farms and Animals

All procedures performed with cows were approved by the Animal Care and Use Committee of Cornell University. Information about farms, animals, and experimental procedures are described in detail in Stangaferro et al. (2018). Briefly, lactating Holstein cows ($n = 2,711$) from 3 commercial dairy farms (A, B, and C) located in New York State were enrolled in this experiment from March 2014 to March 2015. All cows remained in the experiment for up to 18 mo after their calving date unless they left the herd due to sale or death. Average number of milking cows and 305-d milk yield during the experiment were 1,034 cows and 11,067

kg in farm A, 1,248 cows and 11,065 kg in farm B, and 793 cows and 12,221 kg in farm C. Cows were housed in freestall barns with 4 or 6 rows of stalls covered with either mattresses and sawdust bedding (farms A and B) or deep sand bedding (farms A, B and C). Barns had concrete flooring in the feedline and alleyways, self-locking headgates, and fans and sprinklers in the feedline.

Cows in farm A were milked twice daily (approximately every 12 h) until February 2015 and thrice daily thereafter. Cows in farms B and C were milked thrice daily (approximately every 8 h). All farms supplemented cows with recombinant bovine somatotropin (**rbST**; Sometribove zinc, Posilac, Elanco Animal Health, Indianapolis, IN) on a 10- and 11-d schedule until dry off, beginning at 120 (farm A), 110 (farm B), or 65 (farm C) DIM.

Experimental Procedures and Data Collection

The experiment followed a randomized complete block design using parity (primiparous vs. multiparous) as a blocking factor. At 7 ± 3 DIM, cows were blocked by parity and stratified by milk production in the previous lactation (multiparous only), and then randomly assigned to receive first service through timed-artificial insemination (**TAI**) after a VWP of 60 (**VWP60**; $n = 1,352$) or 88 d (**VWP88**; $n = 1,359$). The total number of cows enrolled in the experiment were 1,153 in farm A, 920 in farm B, and 638 in farm C.

Synchronization of ovulation for first service was performed with the Double-Ovsynch (**DO**) protocol (GnRH—7 d—PGF_{2α}—3 d—GnRH—7 d—GnRH—7 d—PGF_{2α}—56 h—GnRH—16 to 20 h—TAI; Souza et al., 2008). Cows were enrolled on a weekly basis (i.e., Fridays on all farms) at 33 ± 3 and 61 ± 3 DIM for the VWP60 and VWP88 treatments, respectively. Thus, cows received TAI at 60 ± 3 and 88 ± 3 DIM in the VWP60 and VWP88 treatments, respectively. For second and greater AI services, cows were inseminated after detection of estrus through visual observation (farms A and C) or a combination of visual observation and physical activity monitoring (farm B) using neck-mounted activity tags (DeLaval Activity Meter System, DeLaval International AB, Tumba, Sweden). Cows failing to conceive to a previous insemination and not reinseminated at a detected estrus 32 ± 3 d after their previous AI were enrolled in the Ovsynch protocol (**D32-Resynch**; GnRH—7 d—PGF_{2α}—56 h—GnRH—16 to 20 h—TAI) for resynchronization of ovulation. On farm C, cows without a corpus luteum ≥ 15 mm in diameter at the time of nonpregnancy diagnosis received the Ovsynch protocol with proges-

terone supplementation [GnRH + controlled internal drug release insert (**CIDR**)—7 d—CIDR removal + PGF_{2α}—56 h—GnRH—16 to 20 h—TAI] as described in Giordano et al. (2016).

Reproductive events and outcomes, milk production (i.e., monthly test-day milk volume and components as a percentage), and date and reason for herd exit (i.e., sold or died) for the 18 mo following calving in the experimental lactation (i.e., lactation in which cows received treatments) were retrieved from the dairy herd management software (DairyComp305, ValleyAg Software, Tulare, CA). If a cow completed the experimental lactation before the end of the 18-mo experimental period, data for the dry period and subsequent lactation were also collected to have data available for a total of 18-mo after calving in the experimental lactation.

Cows that left the herd due to sale or death, were classified as do not breed before 30 DIM, or received their first service TAI outside the DIM range pre-established for their treatment group were excluded from the experiment (87 cows for VWP60 and 99 for VWP88). Therefore, the final number of cows per treatment was 1,265 and 1,260 for the VWP60 and VWP88 treatments, respectively.

Daily Milk and FCM Production Estimation

Individual cow daily milk production for the experimental and subsequent lactation was estimated with the MilkBot model (DairySights LLC, Argyle, NY; Ehrlich, 2011) using monthly milk test data from DHIA tests retrieved from the dairy herd management software. MilkBot is a nonlinear lactation prediction model that predicts individual daily milk yield as a function of DIM and 4 MilkBot parameters: scale, ramp, offset, and decay. Milkbot parameters and daily milk yield calculations have been previously described (Ehrlich, 2011, 2013).

Once daily milk yield was estimated, FCM yield was calculated to estimate daily DMI during lactation. Daily milk yield calculated by the MilkBot model and monthly test milk fat percentage data were used to estimate daily FCM production.

Mathematically,

$$\text{FCM (kg/d)} = 0.4 \times \text{DMW} + 0.15 \\ \times \text{Fat \%} \times \text{DMW},$$

where DMW = daily milk weight (kg/d) estimated by the MilkBot model and Fat % = fat percentage in milk reported by the DHIA in monthly tests. Because daily milk fat percentage data were not available and could not be estimated with MilkBot, data for a specific test

was repeated each day for a 30-d period (e.g., 1st test from 1 to 30 DIM, 2nd test from 61 to 90 DIM, and so on).

BW Estimation

Body weight was modeled daily for every cow using the Korver function as previously described in Van Arendonk (1985):

$$\text{BW (kg)} = A \times \{1 - [1 - (B/A)^{1/3}] \\ \times \exp(-C \times \text{age})\}^3 - (P1/P2) \times \text{DIM} \\ \times \exp(1 - \text{DIM}/P2) + P3^3 \times \text{DPC}^3,$$

where age = cow age in days, A = mature live weight (kg), B = birth weight (kg), C = growth rate, P1 = maximum decrease in live weight during lactation, P2 = time during lactation with minimum live weight, P3 = pregnancy parameter, and DPC = number of days after conception minus 50 (being 0 for the first 50 d of gestation). Data used for average mature live weight (723 kg) and birth weight (40 kg) were retrieved from farm C because data were not available for the other 2 farms. Parameters C, P1, P2, and P3 were 0.004, 30, 60, and 0.0187 for primiparous cows, and 0.006, 50, 80, and 0.0187 for multiparous cows, respectively, based on Kalantari et al. (2010).

DMI Estimation

Daily DMI for individual cows was estimated using NRC (2001) equations. During lactation, DMI was estimated as a function of FCM, BW, and week of lactation (DIM/7), as

$$\text{DMI (kg/d)} = 0.372 \times \text{FCM} + 0.0968 \times \text{BW}^{0.75} \\ \times \{1 - \exp[-0.192 \times (\text{DIM}/7 + 3.67)]\}.$$

During the dry period, DMI was estimated as a percentage of BW, which was calculated using the equation

$$\text{DMI (\% of BW)} = 1.97 - 0.75 \times \exp^{0.16 \times t},$$

where t = days pregnant minus 280.

Values for Input Costs and Revenues

Prices for inputs and outputs were selected to replicate economic conditions representative of the New York State dairy industry during most of the experimental period, which spanned from March 2014 to August 2016. Milk price was the average monthly price

reported by the Dairy Market Watch report (Cornell Cooperative Extension of Chautauqua County, 2017) from March 2014 to August 2016. The weighted average accounting for milk class (class I to IV) price and usage was \$0.41/kg (\$18.53 per hundredweight). Feed cost was set at \$0.29/kg for a lactating cow diet, and \$0.22/kg for a dry and close-up cow diet based on data from the New York Farm Dairy Farm Business Summary from 2014 to 2015 (Knoblauch et al., 2015, 2016).

Newborn calves were given a market value of \$170 for females (Progressive Dairyman, 2017), \$85 for males (i.e., half of the female value), and \$0 for stillborn calves. A value of \$85 per calf was used for male-female twins assuming that females were freemartins.

For reproductive program expense calculations, the cost of GnRH (\$1.60 per dose) and PGF_{2α} (\$2.10 per dose) treatments were calculated based on the market value of 2 commercially available products in New York, whereas the cost of intravaginal progesterone-releasing devices was set at \$10.60 per device based on the cost of the only commercially available product (Eazi-Breed CIDR Cattle Insert, Zoetis, Madison, NJ). Labor cost to apply hormonal treatments was set at \$0.25 per injection, assuming 60 injections per hour, and \$0.75 per CIDR application, assuming application of 20 CIDR devices per hour. The cost of a unit of semen was set at \$10 per dose and the cost to inseminate a cow at \$1 per insemination, assuming 15 inseminations per hour and \$15 per hour for labor. Pregnancy testing was set at \$2.75 per examination based on a cost of \$110 per hour and 40 cows tested per hour. Estrus detection cost was calculated based a total of 2 h of detection per day at \$15 per hour for labor divided by the number of cows in the herd, which resulted on an average of \$0.028/cow per day.

For replacement costs calculations, the market value of a replacement heifer was set at \$1,925 (USDA Economic Research Service, 2017) and the value of beef for cows sold was set at \$1.32/kg based on the average price for good and lean culled cows during the study period (Empire Livestock Marketing, 2016).

Cost of rbST supplementation was \$7 per dose based on the price of the only commercially available product in the United States (Posilac, Elanco Animal Health, 2017) and the labor cost needed to apply the treatments (\$0.25 per injection, assuming 60 injections per hour and \$15/h of labor).

Finally, other operating expenses not accounted for by feeding cost, rbST supplementation, reproductive cost, and replacement cost were set at \$3 per cow per day based on data from accrual operating costs reported in the Dairy Farm Business Summary from 2014 to 2015 (Knoblauch et al., 2015, 2016). The following

items were included in the calculation: hired labor, professional nutritional services, machine repairs, rent and lease, fuel, oil and grease, veterinary and medicine, milk marketing, bedding, milking supplies, utilities, and other professional fees.

Calculation of Economic Outcomes

Two main outcomes were calculated; first, cash flow per cow for the experimental lactation (i.e., the lactation in which the experimental treatments were applied) and subsequent dry period if the cow completed this lactation. For cows that did not leave the herd and calved again, this outcome represents cash flow per calving interval. Second, cash flow per slot for each cow enrolled in the experiment for 18-mo after calving in the experimental lactation, which was conducted to represent the dynamics of a commercial herd, whereby cows that leave the herd are replaced by a first-lactation cow. Therefore, every slot (i.e., stall or unit of space) at the dairy was filled and herd size remained constant. The rationale for this methodology was to allow comparison of the effect of treatments for a fixed period of time, and the choice of 18-mo was to provide sufficient time for cows to complete their experimental lactation, dry period, and generate cash flow data for up to ~150 DIM for the lactation after cows received the experimental treatments. Calculations were based on the assumption that cows in the VWP60 treatment could get pregnant as early as 57 DIM, would have a gestation of ~280 d, and experience a dry period of ~50 to 60 d. In addition, we analyzed the effect of the VWP treatment on revenues and expenses during the 18-mo period after calving only for cows pregnant at first service in the experimental lactation and did not leave the herd up to the end of the 18-mo period after calving. This analysis aimed to explore the effect of achieving pregnancy at 60 ± 3 or 88 ± 3 DIM without the confounding effect of the herd exit dynamics.

For the calculation of cash flow per cow in the experimental calving interval, all revenues (milk sales and calf value) and expenses (feed cost, replacement, reproductive cost, rbST supplementation cost, and other operating costs) were calculated for individual cows for the calving interval or up to the day of herd exit for cows sold and cows that died.

For the calculation of cash flow per slot, we attempted to represent the herd replacement dynamics (i.e., addition of first-lactation cows to replace cows that left the herd due to sale or death) of a dairy herd during an 18-mo period based on the assumption that each slot at the dairy was occupied at all times to maintain herd size. Therefore, for cows that reached the end of

the experiment (i.e., did not leave the herd), costs and revenues were calculated for their experimental lactation (including dry period) and the following lactation up to a total of 18 mo. Conversely, every cow that left the herd before the end of the 18-mo period after calving in the experimental lactation was immediately replaced by a first-lactation cow randomly selected from the data set for the same farm and treatment group in the experiment so that the slot remained occupied with a representative cow (i.e., managed under similar conditions and under similar environmental conditions as during the experiment). Daily costs and revenues for the replacement cow were used to fill the slot up to the end of the 18-mo period. If the replacement left the herd before completion of the 18-mo period, another heifer was randomly selected to replace it. As a result, each slot occupied at the beginning of the experiment remained occupied for 18 mo, as it would be observed in commercial dairy farms.

Total cash flow and cash flow per day of calving interval or per day of the 18-mo period after calving was estimated for each cow using the equation

$$\begin{aligned} \text{Cash flow} = & \text{IOFC} + \text{Calf value} - \text{Replac} \\ & - \text{Repro} - \text{rbST} - \text{OE}, \end{aligned}$$

where IOFC = daily income over feed cost, Replac = cost of replacing cows that left the herd due to sale or death, Repro = cost of applying the reproductive management program, rbST = cost of rbST supplementation, and OE = operating expenses. Daily income over feed cost (**IOFC**) was calculated by subtracting feed cost (i.e., DMI kg $\times$ DM cost per kg) from milk revenue (i.e., milk volume in kg $\times$ milk price per kg) during lactation and the dry period (milk revenue = \$0). Calf value for cows that became pregnant and started a new lactation was the value of the newborn calf (i.e., a one-time revenue when the calf was born). Calves born dead received a value of \$0, whereas calves born alive received market value based on sex.

Replacement costs for every cow that left the herd due to sale or death were assessed on the day the cow left the herd assuming that a replacement heifer replaced the cow immediately. The cost was estimated by subtracting the market value of a replacement heifer from the salvage value of the cow sold and the value of the calf born from the replacement. Thus, the cash cost of replacing a cow was equal to the market value of the replacement heifer minus the salvage value of the replaced cow and the value of the calf born. The salvage value for cows sold was calculated based on their estimated BW on the date of sale times the average beef price. Cows that left the herd due to death were

assigned a salvage value of \$0. The value of the calf born from a replacement heifer was set at \$123 per calf to represent the average calf value for first-lactation cows enrolled in this experiment (accounting for male, female, stillborn, and twins).

Reproductive cost for each AI service for each cow was the aggregation of the cost of hormonal treatments, insemination, detection of estrus during lactation, pregnancy testing (cost added every time a cow was tested for up to 2 times), and labor associated with each activity. Reproductive cost was calculated for the experimental calving interval and for the 18-mo period after calving in the experimental lactation (i.e., included cost during the experimental lactation and subsequent lactation).

The cost of rbST supplementation for the experimental lactation and for the 18-mo period after calving in the experimental lactation was calculated for each cow by multiplying the total number of rbST treatments by the cost per treatment (including hormone and labor cost). The total value for operating expenses was calculated for each cow by multiplying the daily expense by the number of days in lactation and dry period for the experimental lactation, and by 540 d for the calculation of cash flow per slot per 18 mo.

Stochastic Analysis for Input Costs and Value of Outputs

Two stochastic Monte Carlo simulation models (1 for primiparous and 1 for multiparous cows) were developed using @Risk version 7.5 (Palisade Corporation, Ithaca, NY) to estimate differences between treatments in cash flow for the 18-mo period under varying market conditions for the most relevant input costs. Outcomes of interest were the distribution of differences in cash flow between the VWP60 and VWP88 treatments and the contribution of individual input costs to the total variation in cash flow differences.

Reproductive performance, production outcomes, and data for herd exit dynamics from our experiment were used as fixed inputs (Supplemental Table S1; <https://doi.org/10.3168/jds.2018-14484>). Stochasticity in every iteration of the simulation was introduced for milk price, feeding cost, replacement heifers, calf value, beef price, reproductive costs (cost for a first TAI service and cost of second or greater services at detected estrus or TAI), and rbST cost. Values for each parameter are presented in Supplemental Table S2 (<https://doi.org/10.3168/jds.2018-14484>). Monthly milk prices were collected from 2010 to 2017 from the USDA Agricultural Marketing Service (2017). National average dairy feed cost data and beef price of sold cows

were obtained from the University of Wisconsin Dairy Marketing and Risk Management Program for the same period (Gould, 2017a,b). Market value data from 2010 to 2017 for replacement heifers were collected from the USDA Economic Research Service (2017). For calf value, reproductive cost, and rbST price, values were based on a 15% increment and reduction from the average price calculated for this experiment. For example, average calf value was calculated based on the price collected from 2014 to 2016 (\$170 for females and \$85 per male) times the proportion of males, females, stillborn, and twins calved during the 18-mo period (average calf value = \$127.8 per calf born). A range of 15% smaller and greater price was then applied (minimum calf value = \$108.7; maximum calf value = \$147.0). Average values for reproductive and rbST treatment costs used were those observed in the current experiment. Distributions used in the simulations for variables with historical data available (i.e., milk price, feed cost, cost of a replacement heifer, and beef price) were fitted using the BestFit function of @Risk. This function selects the best-fitting distribution based on the lowest value for the Akaike information criteria. Specifically, milk price was fitted with a β distribution, feed cost of a lactating cow diet and a dry cow diet were fitted with uniform distributions, replacement heifer cost was fitted with a triangular distribution, and beef price was fitted with a triangular distribution. For input variables with a minimum, most likely, and a maximum value (calf value, reproductive cost, and rbST price), a pert distribution was used to emphasize the most likely value over the minimum and maximum values (McArt and Oetzel, 2015). Input values for each distribution are presented in Supplemental Table S2.

Simulations were run and recorded for 10,000 iterations with replacement. For each iteration, the difference in cash flow between the VWP60 and VWP88 treatments (output) was calculated as

$$\begin{aligned} &\text{Difference in cash flow (\$ per slot/18 mo)} = \\ &\text{Cash flow VWP88} - \text{Cash flow VWP60.} \end{aligned}$$

Statistical Analysis

All data were analyzed by parity group because of the well-described and expected differences in performance and profitability between primiparous and multiparous cows. Dichotomous outcomes [P/AI at first and at second and greater services; proportion of cows nonpregnant at 350 DIM; proportion of cows that were sold, died, or left the herd (sold plus dead); and proportion of cows that calved again after the end of

the experimental lactation] were analyzed by logistic regression using the GLIMMIX procedure of SAS (version 9.4, SAS Institute Inc., Cary, NC). Time to event data (time to pregnancy and time to herd exit) were analyzed with Cox's proportional hazards models using the PHREG procedure of SAS. A cow was considered pregnant if pregnancy was maintained up to 150 d of gestation. Continuous quantitative outcomes [lactation length, days dry, calving interval, milk yield, DMI, incomes (milk income, calf value, IOFC), expenses (replacement cost, reproductive cost, rbST cost, and other operating costs), and cash flow] were analyzed by ANOVA using the MIXED procedure of SAS.

The effect of treatment (VWP60 and VWP88) was offered as explanatory variable to all models, and farm was included as a random effect. For reproductive performance and herd exit dynamics outcomes, the effect of milk yield accumulated up to 30 DIM (MK30; low, medium, and high based on tertiles from observed data), and the treatment by MK30 interaction were offered to the models. In addition, season of first service (cold = September 21 to June 20, warm = June 21 to September 20; only for first service), and the treatment by season interaction were also offered to the model for P/AI at first service. Results for the effect of MK30 and season of first AI were presented elsewhere (Stangaferro et al., 2018) and are not included in this manuscript except for data for calving interval and proportion of cows that calved again. For outcomes included in profitability analyses (milk production, DMI, all incomes and expenses, and cash flow), the effect of treatment and season of calving (cold = September 21 to June 20; warm = June 21 to September 20) were offered to the models.

For all linear regression models, assumptions of normality and homoscedasticity of variance were evaluated with normal probability plots (normal Q-Q plot) and plots of residuals versus predicted values. For logistic regression models, goodness of fit was evaluated to test for over-dispersion. Graphical examination of the $\log[-\log(\text{survival probability})]$ function obtained from the PROC LIFETEST of SAS was used to assess the proportional hazard assumption for time to event data. The final model for each outcome of interest was selected by backward elimination of explanatory variables with $P > 0.10$ and determination of the lowest value for the Akaike information criterion. Treatment was forced in all models. When appropriate, the least significant different post hoc mean separation test was used to determine differences between least square means.

All proportions reported were generated using the FREQ procedure of SAS, whereas quantitative outcomes were reported as least square means $\pm$ standard

error of the means. All explanatory variables and their interactions were considered significant if $P \leq 0.05$, whereas P -values >0.05 and ≤ 0.10 were considered a tendency.

RESULTS

Reproductive Performance and Herd Exit Dynamics in the Experimental Lactation

Pregnancy per AI at first service was greater ($P < 0.01$) for primiparous cows in the VWP88 (55.3%) than the VWP60 (46.0%) treatment, but similar ($P = 0.16$) between treatments for multiparous cows (Table 1). For second and greater AI services, P/AI was greater ($P = 0.04$) for primiparous cows in the VWP60 (43.6%) than in the VWP88 (37.2%) treatment, but no difference ($P = 0.68$) was observed within the multiparous cow group (Table 1). The hazard of pregnancy during lactation was lower ($P < 0.01$) for cows in the VWP88 than the VWP60 treatment, both in the primiparous ($P < 0.01$) and multiparous cow groups ($P < 0.01$). Conversely, the proportion of nonpregnant cows at 350 DIM did not differ between treatments for primiparous ($P = 0.51$) or for multiparous cows ($P = 0.20$; Table 1).

Primiparous cows in the VWP60 and VWP88 treatment had similar hazard of leaving the herd ($P = 0.56$), and by 350 DIM a similar ($P = 0.58$) total proportion of cows left the herd. On the other hand, multiparous cows in the VWP88 treatment had a greater ($P = 0.03$) hazard of leaving the herd and a greater ($P = 0.03$) proportion of cows left the herd by 350 DIM, primarily because a greater ($P = 0.04$) proportion of cows were sold.

Lactation length was greater for the VWP88 treatment for primiparous ($P < 0.01$), but not for multiparous cows ($P = 0.47$) when all cows were included in the analyses (i.e., cows that completed the experimental lactation and cows that left the herd). When only cows that completed the experimental lactation were included in the analysis, lactation length was longer ($P < 0.01$) for the VWP88 treatment in the primiparous and multiparous group. No differences were observed for dry period duration for primiparous ($P = 0.41$) and multiparous cows ($P = 0.21$).

Calving interval was affected ($P < 0.01$) by treatment, whereby cows in the VWP88 treatment had longer calving interval than cows in the VWP60 treatment (Table 1). Calving interval was also affected by MK30 for both primiparous ($P = 0.03$) and multiparous ($P < 0.01$).

Table 1. Effect of extending the duration of the voluntary waiting period from 60 to 88 DIM on reproductive performance and herd exit dynamics during the experimental lactation

Item	Primiparous			Multiparous		
	VWP60 ¹	VWP88 ²	<i>P</i> -value	VWP60	VWP88	<i>P</i> -value
P/AI ³ 1st service [% (no.)]	46.0 (463)	55.3 (453)	<0.01	36.2 (726)	39.9 (698)	0.16
P/AI 2nd and greater AI [% (no.)]	43.6 (540)	37.2 (494)	0.04	31.5 (1,204)	30.6 (1,015)	0.68
Time to pregnancy after calving						
Hazard ratio (95% CI)	Referent	0.72 (0.63–0.83)	<0.01	Referent	0.76 (0.67–0.84)	<0.01
Mean (d)	115	135	—	142	163	—
Median (d)	85	91	—	104	132	—
NP at 350 DIM ⁴ [% (no.)]	2.3 (480)	2.9 (471)	0.51	11.0 (785)	13.0 (789)	0.20
Time to exit the herd ⁵						
Hazard ratio (95% CI)	Referent	0.89 (0.62–1.30)	0.56	Referent	1.21 (1.02–1.44)	0.03
Mean (d)	324	332	—	302	295	—
Median (d)	—	—	—	—	—	—
Exit the herd [% (no.)]	8.6 (480)	7.8 (471)	0.58	29.9 (785)	35.1 (789)	0.03
Sold [% (no.)]	7.6 (480)	7.2 (471)	0.78	25.5 (785)	30.1 (789)	0.04
Died [% (no.)]	1.8 (480)	1.2 (471)	0.45	4.1 (785)	4.6 (789)	0.87
Lactation length						
All cows (d)	319.4 ± 14.0	341.3 ± 14.0	<0.01	300.7 ± 13.7	305.0 ± 13.7	0.47
Not culled ⁶ (d)	333.0 ± 12.3	354.4 ± 12.4	<0.01	336.2 ± 12.3	356.5 ± 12.3	<0.01
Days dry	53.9 ± 2.7	53.6 ± 2.7	0.41	55.7 ± 4.5	57.3 ± 4.5	0.21
Calving interval (d)	380.4 ± 7.4	399.1 ± 7.4	<0.01	384.0 ± 6.0	403.5 ± 6.0	<0.01
Cows calved again [% (no.)]	86.5 (480)	84.6 (471)	0.37	61.2 (785)	55.0 (789)	0.01

¹VWP60 = first service timed AI at 60 ± 3 DIM after the Double-Ovsynch protocol.

²VWP88 = first service timed AI at 88 ± 3 DIM after the Double-Ovsynch protocol.

³P/AI = pregnancies per artificial insemination.

⁴NP at 350 DIM = percentage of cows not pregnant at 350 DIM.

⁵Time to exit the herd = time (d) from calving until exit the herd because sold or died.

⁶Not culled = cows that did not leave the herd from calving until dry-off in the experimental lactation.

Table 2. Effect of extending the duration of the voluntary waiting period from 60 to 88 DIM on milk production, milk income, DMI, and feed cost during the experimental lactation and dry period

Item	Primiparous				Multiparous			
	VWP60 ¹ (n = 480)	VWP88 ² (n = 471)	Difference ³	P-value ⁴	VWP60 (n = 785)	VWP88 (n = 789)	Difference	P-value
Milk (kg/cow)								
Total	10,972 ± 725	11,805 ± 726	833	<0.01	12,378 ± 721	12,536 ± 721	158	0.53
Daily	33.37 ± 0.91	33.77 ± 0.91	0.40	0.27	40.61 ± 0.62	40.21 ± 0.62	-0.40	0.25
Milk income (\$/cow)								
Total	4,499 ± 297	4,840 ± 298	341	<0.01	5,075 ± 295	5,140 ± 295	65	0.53
Daily	13.68 ± 0.37	13.85 ± 0.37	0.17	0.27	16.65 ± 0.25	16.48 ± 0.25	-0.17	0.25
DMI (kg/cow)								
Milking (total)	7,695 ± 407	8,281 ± 407	586	<0.01	8,132 ± 424	8,277 ± 424	145	0.36
Milking (daily)	23.60 ± 0.33	23.84 ± 0.33	0.24	0.11	26.62 ± 0.14	26.56 ± 0.14	-0.06	0.64
Dry (total)	705.2 ± 32.6	715.6 ± 32.6	10.4	0.32	754.3 ± 60.0	777.5 ± 60.1	23	0.12
Dry (daily)	13.18 ± 0.02	13.27 ± 0.02	0.09	<0.01	13.58 ± 0.02	13.64 ± 0.02	0.06	0.02
Feed cost (\$/cow)								
Milking (total)	2,211 ± 117	2,379 ± 117	168	<0.01	2,337 ± 122	2,378 ± 122	41	0.36
Milking (daily)	6.78 ± 0.10	6.85 ± 0.10	0.07	0.11	7.65 ± 0.04	7.63 ± 0.04	-0.02	0.64
Dry (total)	155.5 ± 7.2	157.8 ± 7.2	2.3	0.32	165.6 ± 13.2	171.4 ± 13.2	6	0.12
Dry (daily)	2.90 ± 0.01	2.92 ± 0.01	0.02	<0.01	2.99 ± 0.01	3.00 ± 0.01	0.01	0.02

¹VWP60 = first service timed AI at 60 ± 3 DIM after the Double-Ovsynch protocol.²VWP88 = first service timed AI at 88 ± 3 DIM after the Double-Ovsynch protocol.³Difference between VWP88 and VWP60 (Difference = VWP88 – VWP60).⁴The effect of season of calving is described in the text.

0.01) cows, because cows in the high-MK30 group had a longer calving interval than cows in the medium- and low-MK30 groups (primiparous: high = 397 ± 7.7 d, medium = 385 ± 7.7 d, low = 388 ± 7.7 d; multiparous: high = 404 ± 6.2 d, medium = 391 ± 6.2 d, low = 386 ± 6.4 d).

For primiparous cows, the proportion of cows that calved after the experimental lactation was similar ($P = 0.37$) between treatments, but it was greater ($P < 0.01$) for cows in the high- (87.4%; 319) and medium- (88.4%; 313) than in the low-MK30 group (80.0%; 319). For multiparous cows, the proportion of cows that calved after the experimental lactation was greater ($P = 0.01$) for the VWP60 treatment, and greater ($P < 0.01$) for cows in the high- (64.3%; 521) and medium- (61.3%; 532) than in the low-MK30 group (48.5%; 521).

Performance and Economic Outcomes During the Experimental Lactation

For primiparous cows, extending the duration of the VWP from 60 to 88 d resulted in greater ($P < 0.01$) total milk yield and income, greater ($P < 0.01$) total DMI and feed cost during the milking period, and greater daily DMI and feed cost during the dry period (Table 2). No differences ($P > 0.10$) were observed for daily milk yield and income, daily DMI and feed cost during the milking period, and total DMI and feed cost during the dry period (Table 2). In addition, primiparous

cows that calved during the warm season had lower ($P < 0.01$) daily milk yield (warm = 33.0 ± 0.9 kg; cold = 34.2 ± 0.9 kg), and income (warm = \$13.5 ± 0.4; cold = \$14.0 ± 0.4) than cows that calved in the cold season. Cows that calved during the warm season also had lower ($P = 0.01$) daily DMI (warm = 23.5 ± 0.3 kg; cold = 23.9 ± 0.3 kg) and daily feed cost (warm = \$6.75 ± 0.10; cold = \$6.89 ± 0.09).

For multiparous cows, the only difference between treatments was for daily DMI ($P = 0.02$) and daily feed cost ($P = 0.02$) during the dry period (Table 2). We did note, however, an effect of calving season, because multiparous cows that calved during the warm season had lower ($P = 0.01$) daily milk yield (warm = 39.9 ± 0.6 kg; cold = 40.9 ± 0.6 kg) and daily milk income (warm = \$16.4 ± 0.3; cold = \$16.8 ± 0.2). Cows that calved during the warm season also tended ($P = 0.08$) to have lower daily DMI (warm = 26.5 ± 0.2 kg; cold = 26.7 ± 0.1 kg) and daily feed cost (warm = \$7.68 ± 0.04; cold = \$7.60 ± 0.04) than cows that calved during the cold season.

The effect of VWP treatment on revenues and expenses during the experimental lactation is presented in Table 3. For primiparous cows, IOFC, rbST cost, and operating expenses were greater ($P < 0.01$) for cows in the VWP88 treatment. The rbST cost was greater because the number of injections received by cows in the VWP88 group (24.5 ± 3.0) was greater ($P < 0.01$) than for cows in the VWP60 group (22.3 ± 3.0). More-

over, cows in the VWP88 group tended ($P = 0.08$) to have greater cash flow (difference between groups = \$89.7 per lactation) than cows in the VWP60 group. No differences between treatments were observed for calf value ($P = 0.32$), replacement cost ($P = 0.60$), reproductive cost ($P = 0.27$), and cash flow per day of CI ($P = 0.42$).

For multiparous cows, we found no effect of treatment on IOFC ($P = 0.60$), calf value ($P = 0.43$), rbST cost ($P = 0.32$), operating expenses ($P = 0.76$), cash flow ($P = 0.62$), and cash flow per day of calving interval ($P = 0.16$; Table 3). Conversely, replacement cost tended ($P = 0.06$) to be greater for the VWP88 treatment and reproductive cost was greater ($P < 0.01$) for the VWP60 treatment (Table 3). No difference was observed for rbST cost because the number of rbST injections received was similar ($P = 0.32$) for both treatments (20.6 ± 3.0 and 21.1 ± 3.0 for VWP60 and VWP88, respectively). Season of calving and the interaction between treatment and season of calving did not affect ($P > 0.10$) any of the parameters evaluated during the experimental lactation for primiparous or multiparous cows.

Performance and Economic Outcomes for 18 mo After Calving in the Experimental Lactation

The effect of treatments on milk yield, milk income, DMI, and feed cost for 18 mo after calving in the experimental lactation is presented in Table 4. All parameters evaluated did not differ ($P > 0.10$) for cows in the VWP60 and VWP88 treatments for the primiparous and multiparous group. In contrast, season of calving affected performance and economic outcomes

of multiparous cows, whereby cows that calved during the cold season in the experimental lactation produced more milk ($P = 0.02$; cold = $20,297 \pm 404$ and warm = $20,069 \pm 409$ kg/cow), generated greater milk income ($P = 0.02$; cold = \$8,320 $\pm$ 166 and warm = \$8,176 $\pm$ 170 per cow), had greater DMI ($P = 0.05$; cold = $13,239 \pm 164$ and warm = $13,177 \pm 168$ kg/cow), and greater feed cost ($P = 0.05$; cold = \$3,804 $\pm$ 47 and warm = \$3,769 $\pm$ 48 per cow) during the milking period than cows that calved during the warm season.

The effect of treatment on revenues and expenses during the 18-mo period after calving is presented in Table 5. For the primiparous group, cows in the VWP60 treatment tended ($P = 0.07$) to have greater replacement cost, had greater ($P < 0.01$) reproductive cost, and had lower ($P < 0.01$) rbST cost than cows in the VWP88 treatment. No differences were observed for the rest of the parameters evaluated ($P > 0.10$). For multiparous cows, reproductive cost was greater ($P < 0.01$) for cows in the VWP60 treatment. Conversely, rbST cost was lower ($P < 0.01$) for cows in the VWP60 group because they received fewer ($P < 0.01$) injections (30.3 ± 3.5 and 31.1 ± 3.6 for the VWP60 and VWP88 group, respectively). No treatment effect was observed for the rest of the parameters ($P > 0.10$) evaluated. Season of calving only affected IOFC for multiparous cows ($P = 0.02$; cold = \$4,401 $\pm$ 131 and warm = \$4,286 $\pm$ 134 per cow).

Further, we analyzed the effect of the VWP treatment on revenues and expenses during the 18-mo period after calving, but only for cows pregnant at first TAI service in the experimental lactation that did not leave the herd up to the end of the 18-mo period after calving. For primiparous cows, a greater ($P < 0.01$) proportion of cows

Table 3. Effect of extending the duration of the voluntary waiting period from 60 to 88 DIM on revenues and expenses during the experimental lactation¹

Item (\$/cow)	Primiparous				Multiparous			
	VWP60 ² (n = 480)	VWP88 ³ (n = 471)	Difference ⁴	P-value ⁵	VWP60 (n = 785)	VWP88 (n = 789)	Difference	P-value
Milk income over feed cost	2,156 $\pm$ 175	2,329 $\pm$ 175	173	<0.01	2,635 $\pm$ 183	2,665 $\pm$ 182	30	0.60
Calf value	99.27 $\pm$ 6.06	103.46 $\pm$ 6.08	4.19	0.32	71.68 $\pm$ 2.55	68.84 $\pm$ 2.54	-2.84	0.43
Replacement cost	143.1 $\pm$ 50.9	156.3 $\pm$ 51.1	13.2	0.60	390.5 $\pm$ 20.0	440.1 $\pm$ 19.9	49.6	0.06
Reproductive cost	60.31 $\pm$ 3.62	58.21 $\pm$ 3.62	-2.10	0.27	63.73 $\pm$ 1.94	58.69 $\pm$ 1.94	-5.04	<0.01
Recombinant bST cost	161.4 $\pm$ 21.8	177.4 $\pm$ 21.8	16.0	<0.01	148.9 $\pm$ 21.9	152.7 $\pm$ 21.9	3.8	0.32
Other operating expenses	1,023 $\pm$ 45	1,083 $\pm$ 45	60	<0.01	941.0 $\pm$ 35.6	946.2 $\pm$ 35.6	5.2	0.76
Cash flow	859.2 $\pm$ 160.6	948.9 $\pm$ 160.7	89.7	0.08	1,164 $\pm$ 130	1,137 $\pm$ 130	-27	0.62
Cash flow per day of calving interval	1.62 $\pm$ 0.57	1.84 $\pm$ 0.57	0.22	0.42	2.24 $\pm$ 0.41	1.81 $\pm$ 0.41	-0.43	0.16

¹Includes milking and dry period.

²VWP60 = first service timed AI at 60 $\pm$ 3 DIM after the Double-Ovsynch protocol.

³VWP88 = first service timed AI at 88 $\pm$ 3 DIM after the Double-Ovsynch protocol.

⁴Difference between VWP88 and VWP60 (Difference = VWP88 - VWP60).

⁵The effect of season of calving is described in the text.

Table 4. Effect of extending the duration of the voluntary waiting period from 60 to 88 DIM on milk production, milk income, DMI, and feed cost during 18 mo after calving in the experimental lactation

Item	Primiparous				Multiparous			
	VWP60 ¹ (n = 480)	VWP88 ² (n = 471)	Difference ³	P-value ⁴	VWP60 (n = 785)	VWP88 (n = 789)	Difference	P-value
Milk (kg/slot ⁵)	18,185 ± 378	18,227 ± 378	42	0.79	20,166 ± 409	20,069 ± 409	−97	0.49
Milk income (\$/slot)	7,456 ± 155	7,473 ± 155	17	0.79	8,268 ± 168	8,228 ± 168	−40	0.49
DMI (kg/slot)								
Milking	12,226 ± 120	12,303 ± 120	77	0.21	13,165 ± 166	13,191 ± 166	26	0.66
Dry	693.8 ± 33.9	703.1 ± 34.0	9.3	0.41	723.1 ± 49.8	728.9 ± 49.9	5.8	0.71
Feed cost (\$/slot)								
Milking	3,512 ± 34	3,535 ± 34	23	0.21	3,783 ± 48	3,790 ± 48	7	0.66
Dry	153.0 ± 7.5	155.0 ± 7.5	2.0	0.41	159.4 ± 11.0	160.7 ± 11.0	1.3	0.71

¹VWP60 = first service timed AI at 60 ± 3 DIM after the Double-Ovsynch protocol.²VWP88 = first service timed AI at 88 ± 3 DIM after the Double-Ovsynch protocol.³Difference between VWP88 and VWP60 (Difference = VWP88 − VWP60).⁴The effect of season of calving is described in the text.⁵Slot is the unit of space occupied by each cow enrolled in the experiment for an 18-mo period after calving in the experimental lactation.

in the VWP88 group (41%; 192/471) compared with the VWP60 (31%; 147/480) met the eligibility criteria. Cows in the VWP88 treatment tended to have greater IOFC (~\$127/cow; $P = 0.10$), greater calf value (~\$10/cow; $P = 0.07$), and greater cash flow total (~\$138/slot per 18 mo; $P = 0.08$) and per day (~\$0.25/cow per day; Table 6). No effect of treatment was observed for the rest of the parameters evaluated ($P > 0.10$).

Multiparous cows pregnant at first TAI service in the experimental lactation that did not leave the herd up to the end of the 18-mo period after calving represented 19 (149/785) and 17% (136/789) of the total multiparous cows enrolled in the VWP60 and VWP88 group, respectively ($P = 0.37$). No effect of treatment on any of the parameters evaluated was observed for

multiparous cows pregnant at first service (Table 6). Only season of calving affected IOFC ($P = 0.04$; cold = \$4,904 ± 157 and warm = \$4,680 ± 167 per slot per 18 mo), cash flow ($P = 0.04$; cold = \$3,222 ± 136 and warm = \$3,001 ± 148 per slot per 18 mo), and cash flow per day ($P = 0.04$; cold \$6.97 ± 0.25 and warm = \$5.56 ± 0.27 per slot per 18 mo).

Stochastic Analysis

For primiparous cows, differences in cash flow under diverse pricing scenarios were always in favor of the VWP88 group. Cash flow differences ranged from a minimum of \$0.9 to a maximum of \$114.4 per slot per 18 mo (Figure 1A). The average difference in cash flow

Table 5. Effect of extending the duration of the voluntary waiting period from 60 to 88 DIM on revenues and expenses during 18 mo after calving in the experimental lactation

Item (\$/slot ¹)	Primiparous				Multiparous			
	VWP60 ² (n = 480)	VWP88 ³ (n = 471)	Difference ⁴	P-value ⁵	VWP60 (n = 785)	VWP88 (n = 789)	Difference	P-value
Milk income over feed cost	3,806 ± 119	3,803 ± 119	−3	0.95	4,363 ± 132	4,324 ± 132	−39	0.38
Calf value	100.5 ± 3.5	102.9 ± 3.5	2.4	0.59	80.78 ± 2.52	77.98 ± 2.52	−2.80	0.43
Replacement cost	327.3 ± 52.1	259.0 ± 52.3	−68.3	0.07	624.9 ± 31.4	673.6 ± 31.3	48.7	0.16
Reproductive cost	97.58 ± 1.38	91.28 ± 1.40	−6.30	<0.01	104.14 ± 1.95	93.63 ± 1.95	−10.51	<0.01
bST cost	215.9 ± 23.6	221.6 ± 23.6	5.7	<0.01	219.4 ± 25.6	224.9 ± 25.6	5.5	<0.01
Other operating expenses	1,512	1,512	—	—	1,512	1,512	—	—
Cash flow	1,756 ± 148	1,824 ± 148	68	0.32	2,006 ± 124	1,921 ± 124	−85	0.19
Cash flow per day	3.25 ± 0.28	3.37 ± 0.28	0.12	0.32	3.71 ± 0.23	3.56 ± 0.23	−0.15	0.19

¹Slot is the unit of space occupied by each cow enrolled in the experiment for an 18-mo period after calving in the experimental lactation.²VWP60 = first service timed AI at 60 ± 3 DIM after the Double-Ovsynch protocol.³VWP88 = first service timed AI at 88 ± 3 DIM after the Double-Ovsynch protocol.⁴Difference between VWP88 and VWP60 (Difference = VWP88 − VWP60).⁵The effect of season of calving is described in the text.

Table 6. Effect of extending the duration of the voluntary waiting period from 60 to 88 DIM on revenues and expenses during 18 mo after calving in the experimental lactation for cows pregnant at first service that did not leave the herd

Item (\$/slot ¹)	Primiparous				Multiparous			
	VWP60 ²	VWP88 ³	Difference ⁴	P-value ⁵	VWP60	VWP88	Difference	P-value
Milk income over feed cost	3,906 ± 145	4,033 ± 143	127	0.10	4,854 ± 161	4,730 ± 161	−124	0.23
Calf value	118.6 ± 4.5	128.5 ± 4.1	9.9	0.06	118.1 ± 3.9	125.0 ± 4.0	6.9	0.22
Reproductive cost	82.41 ± 1.89	81.32 ± 1.76	−1.09	0.60	83.97 ± 2.14	79.94 ± 2.15	−4.03	0.11
bST cost	210.6 ± 24.5	211.3 ± 24.5	0.7	0.19	209.5 ± 26.9	208.0 ± 26.9	−1.5	0.21
Other operating expenses	1,512	1,512	—	—	1,512	1,512	—	—
Cash flow	2,218 ± 119	2,356 ± 116	138	0.08	3,167 ± 141	3,056 ± 141	−111	0.28
Cash flow per day	4.11 ± 0.22	4.36 ± 0.22	0.25	0.08	5.87 ± 0.26	5.66 ± 0.26	−0.21	0.28

¹Slot is the unit of space occupied by each cow enrolled in the experiment for an 18-mo period after calving in the experimental lactation.

²VWP60 = first service timed AI at 60 ± 3 DIM after the Double-Ovsynch protocol.

³VWP88 = first service timed AI at 88 ± 3 DIM after the Double-Ovsynch protocol.

⁴Diff = difference between VWP88 and VWP60 (Difference = VWP88 − VWP60).

⁵The effect of season of calving is described in the text.

after 10,000 iterations was \$50.4 per slot per 18 mo (95% CI = \$18.2 to \$88.7 per slot per 18 mo). The cost of a replacement heifer was the main contributor to the total variance, explaining ~65% of the total variation in cash flow differences. Beef price for cows sold was the second most important factor and explained another ~27% of the total variation (Figure 1B). Therefore, these 2 factors combined explained ~92% of the total variation in cash flow differences.

For multiparous cows, differences in cash flow after 10,000 iterations were always detrimental for the VWP88 group, with a mean of −\$56.6 per slot per 18 mo (95% CI = −\$89.5 to −27.3 per slot per 18 mo), and a minimum and maximum of −\$89.5 and −27.3 per slot per 18 mo, respectively (Figure 2A). The contribution to variance was led by the cost of a replacement heifer (47.4%) followed by beef price (45.2%), and both combined represented ~93% of the total variation in cash flow differences (Figure 2B).

DISCUSSION

We evaluated the effect of extending the VWP from 60 to 88 DIM on cow profitability, accounting for the multiple interactions among reproductive performance, productivity, and herd replacement dynamics. In agreement with previous studies (Van Amburgh et al., 1997; Arbel et al., 2001; Gobikrushanth et al., 2014), the greatest effect of extending the VWP on reproductive performance was shifting timing of pregnancy toward later lactation. For primiparous cows in the VWP88 group, pregnancy was delayed in spite of greater P/AI to first service. Cows with shorter VWP fully compensated for reduced first service P/AI through earlier and more frequent opportunities for reinsemination. A direct

consequence of delayed pregnancy in the primiparous cow group was longer lactations (for all cows or only cows not culled) and extended calving intervals. For the multiparous group, overall time to pregnancy was also delayed. Nevertheless, we observed longer calving intervals and longer overall lactation length for nonculled cows only. This was because another consequence of delayed first service was a greater proportion of cows removed from the herd. Delayed pregnancy and greater culling pressure in older cows (DeVries et al., 2010; Pinedo et al., 2010) likely contributed to the greater proportion of cows culled in this group. As more cows left the herd earlier, their shorter lactations resulted in smaller differences between groups for lactation length.

In primiparous cows, total cash flow for the calving interval of the experimental lactation tended to be greater for the VWP88 than the VWP60 group, because extended lactations resulted in a substantial IOFC increment not offset by greater rbST cost and OE (all affected by lactation length). On the other hand, parameters that did not depend on lactation length, such as calf value, replacement cost, and the cost of implementing reproductive programs, were similar because we found either no differences or negligible differences between groups for calves born, replacement dynamics, and number of AI services. Unlike total cash flow for the calving interval, cash flow per day was similar likely because of the high persistency of lactation of primiparous cows (Stanton et al., 1992; Scott et al., 1996; Van Amburgh et al., 1997), which resulted in high IOFC in late lactation. Collectively, our data suggested that, for primiparous cows, extending lactation length by delaying first service increased total cash flow per calving interval. This effect was primarily due to more productive days, because cash flow per day was

similar due to the high milk production persistency of primiparous cows. This is particularly relevant when considering extrapolation of our results to other farms and conditions, because in our experiment all cows received rbST supplementation, which is known to increase lactation persistency (Peel and Bauman, 1987; Chalupa and Galligan, 1989; Bauman and Vernon, 1993). Without rbST supplementation it is likely that

the differences observed would have been reduced and favored the group with shorter VWP.

Unlike for primiparous cows, the lack of difference in total cash flow per calving interval or per day of the calving interval for the multiparous cow group was a reflection of the similar lactation length for the VWP treatments when all cows enrolled (i.e., culled and not culled) were accounted for. Additional monetary differ-

Figure 1. (A) Relative frequency distribution for differences in cash flow (\$ per slot/18 mo; slot is the unit of space occupied by each cow enrolled in the experiment for an 18-mo period after calving in the experimental lactation) for primiparous cows in the VWP88 (first service timed AI at 88 ± 3 DIM after the Double-Ovsynch protocol) and VWP60 (first service timed AI at 60 ± 3 DIM after the Double-Ovsynch protocol) treatments for 10,000 iterations of stochastic simulation. Differences in cash flow were calculated by subtracting cash flow for the VWP60 from the VWP88 treatment. (B) Tornado graph depicting the contribution to variance in percentage for nonfixed variables included in the stochastic simulation model. Color version available online.

ences associated with the replacement dynamics and reproductive performance balanced overall cash flow differences between treatments. For example, the small numerical increment in IOFC, along with the reduction in reproductive program cost for cows in VWP88, offset the lower calf value and the minor extra cost of rbST and OE. Nevertheless, that was insufficient to com-

pensate for greater replacement cost. Greater culling pressure for multiparous cows in the extended VWP treatment not only limited the potential IOFC benefits of longer lactation, but also negatively affected cash flow by increasing replacement cost. Others have also documented major contributions of replacement cost to differences in overall cash flow of cows managed with

Figure 2. (A) Relative frequency distribution for differences in cash flow (\$ per slot/18 mo; slot is the unit of space occupied by each cow enrolled in the experiment for an 18-mo period after calving in the experimental lactation) for multiparous cows in the VWP88 [first service timed AI (TAI) at 88 ± 3 DIM after the Double-Ovsynch protocol] and VWP60 (first service timed AI at 60 ± 3 DIM after the Double-Ovsynch protocol) treatments for 10,000 iterations of stochastic simulation. Differences in cash flow were calculated by subtracting cash flow for the VWP60 from the VWP88 treatment. (B) Tornado graph depicting the contribution to variance in percentage for non-fixed variables included in the stochastic simulation model. Repro = cost of applying the reproductive management program. Color version available online.

different VWP duration (Schmidt, 1989; Inchaisri et al., 2011; Gobikrushanth et al., 2014). Taken together, our results for multiparous cows and those from previous experiments emphasize the importance of considering the complex interactions between reproductive outcomes, productive performance, and the herd exit dynamics when evaluating the economic consequences of manipulating the duration of the VWP for dairy herds.

Although many studies reported the economic value of reproductive management strategies for dairy cattle (Groenendaal et al., 2004; Tenhagen et al., 2004; Meadows et al., 2005; Olynk and Wolf, 2009; Giordano et al., 2011, 2012), specific criteria or methods to measure dairy cow profitability have not been clearly established. We included evaluations of cash flow for the calving interval of individual cows and for an 18-mo period after calving in the experimental lactation for each slot filled at the beginning of the study. The latter analysis was used because evaluating profitability for a single calving interval does not account for the effect of timing of pregnancy on the subsequent lactation of cows (Arbel et al., 2001; Giordano et al., 2012; Gobikrushanth et al., 2014). In addition, evaluating slots rather than cows allows accounting for the performance of the replacement that filled a slot after another cow left the herd. This is relevant because replacement cows not only have different IOFC, but also different pregnancy and herd exit risk than the cow they replaced (DeLorenzo et al., 1992; Hadley et al., 2006; Dhuyvetter et al., 2007). Thus, the analysis per slot per 18 mo may better represent the reality of dairy farms that maintain a constant herd size by immediately replacing cows that leave the herd in an attempt to maximize profitability per unit of time (DeVries, 2004, 2006b). A caveat of the analysis used in our study is that only a portion of the productive life of cows was included; hence, future research should consider monitoring cow performance for a fixed period of time representative of the expected lifetime of cows.

For primiparous cows, the lack of difference between treatments in total cash flow reflected the compensation for additional productive days in the first lactation by more productive days in the early portion of the subsequent lactation (i.e., second lactation). The \$173 greater IOFC due to ~20 d longer experimental lactations for cows in the VWP88 treatment was fully compensated by a similar number of productive days in the subsequent lactation. This was because dry period length was similar between groups and IOFC per day was of approximately the same magnitude at the end of the experimental lactation than in the early part of the subsequent lactation. Additional compensation

between the extra cost of rbST supplementation for the VWP88 treatment (had more days in later lactation) and greater cost of the reproductive program in the VWP60 treatment (due to more AI services) made replacement cost the greatest contributor to differences between treatments. Unexpectedly, a greater proportion of second-parity cows (received experimental treatment as primiparous cows) in the VWP60 treatment left the herd in early lactation, increasing replacement cost for the 18-mo period. In part, this difference could be explained by a slightly greater period at risk of culling in the subsequent lactation and more cows leaving the herd due to udder health problems and other health disorders in early to mid lactation (data not shown; $P > 0.05$).

Minor monetary differences and compensation among items included in the analysis also explained the lack of differences in total cash flow for the 18-mo period for multiparous cows. Nevertheless, most items evaluated trended in favor of the shorter VWP treatment. This was expected because of the greater replacement cost in the experimental lactation and the lesser benefit of extended lactations on IOFC for multiparous cows in the VWP88 treatment. Less persistent lactations for multiparous cows (Stanton et al., 1992; Scott et al., 1996; Van Amburgh et al., 1997) favor profitability in early lactation more than for primiparous cows transitioning from first to second lactation because of the substantial difference in IOFC between early and late lactation for multiparous cows. Overall, our results disagree with some previous studies that recommended longer VWP for multiparous cows because of expected increases in profitability (Van Amburgh et al., 1997; Arbel et al., 2001). Nevertheless, those studies included assumptions about herd replacement dynamics, multiple exclusion criteria (i.e., enrolled only second-lactation cows or cows that did not calve during summer months and only cows with above-average milk production), and different methods to calculate profitability (e.g., per cow instead of per slot), which could explain the contradictory results.

The lack of significance for differences in cash flow in spite of the large number of cows included in the experiment was likely a reflection of the major variation in profitability per slot, ranging from -\$2,503 to \$5,599 (data not shown). This major disparity in cash flow was explained primarily by large differences in replacement costs between slots in which the cow did not leave the herd during the 18-mo period (i.e., replacement cost was \$0) versus those in which cows were replaced 1 or more times. Indeed, an interesting observation from the stochastic analysis was that 2 of the main factors that determine total replacement cost (i.e., replacement

heifer price and beef price) were the major contributors to differences in cash flow between VWP treatments. The effect of the replacement dynamics on the cow population in the subsequent lactation also affected results, because more replacements entering the herd in the subsequent lactation for the VWP60 treatment resulted in a greater proportion of first parity cows filling up slots by the end of the 18-mo period. This may have explained, at least in part, why more DIM of the 18-mo period filled with cows in their second lactation did not translate into major IOFC benefits in the subsequent lactation for primiparous cows in the VWP60 treatment.

The duration of the VWP has a substantial effect on time to pregnancy for cows that become pregnant to first service, in particular if cows are submitted to first service with all TAI programs. As P/AI to first service increases, lactation length and the calving interval are locked for a greater proportion of cows in the herd. Our analysis for cows that became pregnant at first service only was meant to provide insights about the effect of timing of pregnancy during lactation on cow profitability. It also allowed visualizing, albeit indirectly, the effect of herd exit dynamics on profitability, because only cows that did not leave the herd during the 18-mo period after calving were included in the analysis. Greater cash flow for primiparous cows inseminated at 88 rather than 60 DIM is in line with the concept that high-producing cows with persistent lactations benefit by pregnancy closer to 100 than 50 DIM (DeVries, 2006a; Inchaisri et al., 2011). On the other hand, the opposite was observed for multiparous cows, suggesting that, through increased IOFC, pregnancy at 60 DIM was more profitable than at 88 DIM. As the monetary differences for most items were very similar and replacement costs were not accounted for, IOFC was the main contributor to cash flow differences between treatments. This was due to the substantial difference in IOFC between early and late lactation for multiparous cows. Our results are in agreement with previous studies that recommended shorter calving intervals to maximize milk production and profitability of dairy cows (Olds et al., 1979; Oltenacu et al., 1981; Dijkhuizen et al., 1985; Holmann et al., 1984; Schmidt, 1989). The similar trends for differences between treatments when only cows pregnant to first service and all cows in the study were evaluated provides additional evidence that the VWP duration and time to pregnancy that maximize cow profitability can be different for primiparous and multiparous cows.

Results from the stochastic analysis for both primiparous and multiparous cows confirmed that the direction of differences between treatments remained in

spite of variable prices for major inputs and sources of revenues. Moreover, after 10,000 simulations of different pricing scenarios, results did not favor the VWP60 treatment for primiparous cows or the VWP88 treatment for multiparous cows. Therefore, an 88-d VWP for primiparous and a 60-d VWP for multiparous cows, as compared with the alternative in our study, should provide a benefit under a wide range of economic conditions. Interestingly, the major contributors (>90%) to differences between treatments were factors related to the herd replacement dynamics (i.e., replacement heifer price and beef price). Thus, culling policies as well as current and future prices for replacements and the salvage value of cows sold are important considerations when defining the duration of the VWP for a particular dairy herd. In addition, the agreement for results of the stochastic analysis and the main findings of our study emphasized the relevance of accounting for the herd exit dynamics when comparing the profitability of different VWP durations.

CONCLUSIONS

We conclude that dairy farms using aggressive reproductive management programs that result in high P/AI to first service might benefit by extending the duration of the VWP beyond 60 d for primiparous cows. First insemination at around 88 DIM may result in greater profitability per slot per unit of time. On the other hand, a VWP in the range of 60 rather than 88 DIM might be preferred for multiparous cows. In addition, our data suggested that decisions about VWP duration for dairy cows should be made with careful consideration of the complex interactions between replacement dynamics and the productive and reproductive performance of dairy cows in multiple lactations. Finally, this study also emphasized the need to standardize the methods used to calculate the effect of reproductive management strategies on cow and herd profitability if decision-making of on-farm practices is to be based on this type of research.

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