Targeted reproductive management for lactating Holstein cows: Economic return

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ABSTRACT

Targeted reproductive management (TRM), employing automated monitoring devices (AMD), is as an alternative to the blanket adoption of ovulation synchronization protocols (OvSP) for first postpartum AI and a means of reducing the use of OvSP for re-insemination of nonpregnant cows. We hypothesized that a TRM that relies heavily on AI of cows on AMD-detected estrus improves reproductive performance and economic return. Early-postpartum estrus characteristics (EPEC) of multiparous (n = 941) cows were evaluated at 40 and 41 DIM (herds 1 and 2, respectively) and EPEC of primiparous (n = 539) cows were evaluated at 54 and 55 DIM (herds 1 and 2, respectively). Cows in the control treatment were enrolled in the Double-Ovsynch protocol and AI at a fixed time (TAI) at 82 and 83 DIM (primiparous cows in herds 1 and 2, respectively) and 68 and 69 DIM (multiparous in herds 1 and 2, respectively). Cows enrolled in the TRM treatment were managed according to EPEC as follows: (1) cows with ≥1 intense estrus (heat index ≥70; 0 = minimum, 100 = maximum) were AI upon AMD-detected estrus starting at 64 (primiparous) and 50 (multiparous) DIM and, if not AI, were enrolled in the Double-Ovsynch, (2) cows without an intense estrus were enrolled in the Double-Ovsynch at the same time as cows in the control treatment. Control cows were re-inseminated based on visual or patch-aided detection of estrus, whereas TRM cows were re-inseminated as described for control cows with the aid of the AMD. All cows received a GnRH injection 27 ± 3 d after AI and, if diagnosed as nonpregnant, completed the 5-d CoSynch protocol and received TAI 35 ± 3 d after insemination. The hazard of pregnancy was greater for cows in the TRM treatment (adjusted hazard ratio = 1.17, 95% CI = 1.05, 1.32), resulting in more cows from the TRM treatment starting a new lactation (82.6% vs. 77.2%) and fewer of them sold (15.5% vs. 20.8%). Treatments did not differ regarding total milk yield (control = 12,782.1 ± 130.6 kg, TRM = 13,054.7 ± 136.1 kg). The gross profit [(milk income + sale value + subsequent lactation calf value) − (feed cost + replacement cost + fixed cost + reproductive management cost)] of cows in the TRM treatment was $108 greater than the control treatment ($3,061.6 ± $45.9 vs. $2,953.8 ± $45.2). According to a Monte Carlo stochastic simulation, the mean (±SD) difference in gross profit was $87.8 ± 12.6/cow in favor of the TRM treatment, and 95% of the scenarios ranged from $67.2/cow to $108.5/cow (minimum = $30.2/cow, maximum = $141.1/cow). Under the conditions of the current experiment, the TRM treatment improved the gross profit of Holstein cows because the increased hazard of pregnancy changed culling dynamics, reducing replacement cost and cow sales and increasing calf value. The findings of the current experiment emphasize the importance of efficient reproductive management and its substantial economic implications, particularly in the context of high-producing Holstein cows.

Key words: Holstein cow, reproduction, automated estrous detection, gross profit

INTRODUCTION

Economic return of dairy herds is largely explained by efficient production of milk and reduced feeding costs. In fact, Evink and Endres (2017) demonstrated that 98.6% of annual revenue comes from milk sales and 51.7% of annual production costs comes from feeding lactating cows. The aim of reproductive management in dairy herds is to establish pregnancies within an interval postpartum that maximizes efficient milk production throughout the lactation (e.g., income over feed cost; **IOFC**), reduces the likelihood of culling due to reproductive failure, and increases production of replacement animals. Several studies have analyzed the economic impact of varying 21-d pregnancy rates (**21-d PR**) on herd profitability

(Giordano et al., 2011, 2012; Cabrera, 2012; Galvão et al., 2013). The 21-d PR is a function of a herd's voluntary waiting period, 21-d insemination rate, pregnancy per AI, and pregnancy loss. It provides a dynamic measure of the speed at which eligible cows become pregnant after the voluntary waiting period. These investigations demonstrate a direct correlation between changes in 21-d PR and herd economic net returns. Increases in 21-d PR from 10% to ~30% almost always produce large economic benefit per cow, whereas the economic gains from increments in 21-d PR beyond 30% are less. Thus, 21-d PR is generally assumed to follow the principles of diminishing returns. For example, Cabrera (2012) found that increasing the 21-d PR from 10% to 15% leads to an additional annual net return of approximately $14.4 per cow. However, when the 21-d PR rises from 35% to 40%, the economic benefit drops significantly, resulting in a smaller increase of just $3.2 per cow annually. This illustrates that although early improvements in pregnancy rates yield substantial financial gains, further increases at higher pregnancy rates provide diminishing economic returns. Consequently, maximizing herd profitability involves balancing reproductive performance improvements with the associated costs of management interventions to increase the 21-d PR.

Several advancements in reproductive management have been made in the past 30 years, including ovulation synchronization protocols (**OvSP**) and fixed-time AI and automation of estrous detection (Wiltbank and Pursley, 2014; Brito et al., 2021; Fricke and Wiltbank, 2022). Of particular relevance to the advancements in rate of AI was the introduction of sequential injections of exogenous hormones (e.g., GnRH and $PGF_{2\alpha}$) that tightly synchronize ovulation and allow for timed AI (**TAI**). The use of TAI results in the systematic AI of cows at predetermined intervals postpartum, which all but guarantees that cows are AI at least once within a timeframe after calving that will help reach pregnancy at an optimal time during lactation. Some have suggested that a need exists to reduce the use of exogenous reproductive hormones in the management of lactating dairy cows because of public perception. Pieper et al. (2016), in a small survey conducted in Germany, reported that 65% of respondents disapproved of the use of hormone treatment to increase fertility. More importantly, strategically reducing the percentage of cows submitted to OvSP reduces the number of times cows are handled, likely facilitating labor.

The majority (87%) of dairy herds in the United States adopt detection of estrus as part of their reproductive management according to the USDA (2014). Accurate detection of estrus and timely AI in relation to the expected ovulation are pivotal to achieving adequate pregnancies per AI (**P/AI**; Galvão et al., 2013). Cow (i.e., diseases, milk yield; Lopez et al., 2004; Walker et al., 2008; Aung-

ier et al., 2012) and environmental (i.e., heat stress, overstocking; Tippenhauer et al., 2021) factors often hamper estrous behavior and detection. Automated estrous detection devices have become accessible in recent years and may become more popular in the future. Researchers have demonstrated that automated monitoring devices (**AMD**) may increase the rate of AI, P/AI, and pregnancy rates compared with visual detection of estrus (Marques et al., 2020). Furthermore, researchers have demonstrated that the combined use of AMD and OvSP + TAI for first postpartum AI and re-insemination improved some measures of reproductive performance compared with OvSP + TAI alone (Fricke et al., 2014; Dolecheck et al., 2016b; Denis-Robichaud et al., 2018). In a recent retrospective study, Borchardt et al. (2021) reported that cows detected in estrus by an AMD from 7 to 40 DIM had increased hazard of pregnancy within 200 DIM. Thus, a novel use has been proposed for AMD: targeted reproductive management (**TRM**) to identify cows that more promptly return to cyclicity postpartum and are, therefore, more likely to express estrus and become pregnant. Fricke et al. (2014) demonstrated that cows selectively assigned to start the OvSP at different intervals after calving according to their estrous behavior by 50 DIM had similar reproductive performance to those assigned to traditional reproductive management independent of their resumption of estrous activity. In a recent study, Rial et al. (2022) compared reproductive performance between cows managed to prioritize AI at detected estrus and those managed solely through OvSP. Although P/AI was highest among cows managed solely with OvSP, pregnancy rates were higher among cows managed to prioritize AI at detected estrus due to earlier re-insemination. We recently evaluated a TRM in which cows that had an intense estrus (heat index ≥70) within 40 to 55 DIM were allowed to be inseminated at AMD-detected estrus and those that did not have an intense estrus were subjected to OvSP + TAI (Gonzalez et al., 2023). The likelihood of pregnancy was lower when primiparous cows with an intense estrus were inseminated at AMD-detected estrus compared with those subjected to OvSP and TAI but, because of faster re-insemination, the hazard of pregnancy up to 305 DIM was greater for cows in the TRM treatment compared with a treatment that relied heavily on OvSP + TAI.

We hypothesized that the gross profit (**GP**) at the end of the lactation is greater for cows subjected to a TRM that increases the reliance on insemination at AMD-detected estrus throughout the lactation as a consequence of improved reproductive performance and reduced use of reproductive hormones. The aim of this experiment was to compare the GP per lactation of cows under a TRM that favors AI on AMD-detected estrus compared with cows under a reproductive management that favors OvSP and TAI.

MATERIALS AND METHODS

This experiment was conducted from January 2020 until June 2023. Cows from herd 1 calved between January and August of 2020 and those from herd 2 calved between March and June of 2021. Cows from herd 1 and 2 were followed until December of 2021 and June of 2023, respectively, or until they were removed (death/ sale) from the herd. All procedures involving animals were approved by the animal care and use committee of the University of Florida (#202111375).

Animals, Housing, and Management

Cows (n = 1,930) from 2 commercial dairies located in north-central Florida were enrolled in this experiment. Herd 1 had ~3,100 lactating cows, which were milked thrice daily in a rotary parlor, and had a rolling herd milk yield average of 41 kg/d. Herd 2 had ~5,500 lactating cows, which were milked thrice daily in a parallel parlor, and had a rolling herd milk yield average of 44 kg/d. Cows in herd 1 were housed in naturally ventilated, sand-bedded, freestall barns with 2 rows of freestalls per pen. All pens were fitted with sprinklers over the feed bunk and fans over the feed bunk and stalls. In herd 2, pre-partum cows were housed in naturally ventilated barns equipped with sprinklers over the feed bunk and fans over the feed bunk and stalls; whereas, postpartum cows were housed in tunnel-ventilated barns equipped with high-pressure misters on the air inlet end of the barn and sprinklers over the feed bunk. Pens in herd 2 had 3 rows of sand-bedded freestalls. In both herds, primiparous and multiparous cattle were housed separately during the prepartum and postpartum periods. A TMR formulated to meet or exceed the nutritional requirements according to animal category and milk yield (NRC, 2001) was offered twice daily. The main ingredients of postpartum diets were corn silage, alfalfa hay, corn meal, soybean meal, cotton seed, and a mineral mix. The on-farm herd management software programs used were Dairy Comp 305 (Valley Ag Software, Tulare, CA) and PCDART (Dairy Records Management Systems, Raleigh, NC) in herds 1 and 2, respectively.

Automated Monitoring Devices and Estrous Characteristics

Throughout the experiment, the activity thresholds for estrus were constant and the same for the 2 collaborating herds. University of Florida personnel reviewed reports generated by DataFlow2 software (Allflex Livestock Intelligence, Madison, WI) and containing cows deemed to be in estrus daily at 0600, 1400, and 2200 h. University of Florida personnel evaluated the activity and rumination graphs of each cow deemed in estrus by the DataFlow2 software and recorded rumination nadir (maximum difference in rumination time within a 2-h period compared with previous days), activity peak (0 = minimum, 100 = maximum), and heat index (0 = minimum, 100 = maximum). To calculate estrous duration, University of Florida personnel recorded the time of onset (2-h period when activity surpassed the activity threshold) and end (2-h period when the activity fell below the activity threshold) of estrus. The AMD was removed from cows in the control treatment 7 ± 3 d after the first AI, whereas the AMD of cows in the TRM treatment were removed when they were diagnosed pregnant 67 ± 3 d after AI, when they were deemed not eligible for AI by the herds' managers, when they were sold or died, or when they reached 305 d postpartum, regardless of reproductive status. Throughout the experiment, farm personnel were not informed of AMD-detected alterations in rumination and health index to prevent bias.

Experimental Design

This experiment had a randomized complete block design with cow as the experimental unit. Primiparous (n = 679) and multiparous (n = 1,251) Holstein animals were enrolled in the experiment, ~30 d before the expected calving date (d 0 = calving). At enrollment, all animals were fitted with an AMD (Allflex Livestock Intelligence, Madison, WI). Cows were blocked by lactation number (0, 1, and ≥2). Primiparous cows were ordered by stage of gestation and multiparous cows were ordered for previous lactation 305-d milk yield. Study personnel (T. D. Gonzalez) used the random function in Microsoft Excel (Microsoft Corp., Redmond, WA) to allocate, within block, cows into the control and TRM treatments. Cows diagnosed as nonpregnant before calving (n = 18), deemed not eligible for AI by the herd's manager (n = 132), removed from the herd (n = 169), that had damaged straps (n = 73), that had defective AMD (n = 7), and that did not follow the assigned treatment (n = 51) were excluded from the experiment.

First Insemination. All cows in the control treatment (n = 749) were submitted to the Double-Ovsynch protocol (d 0, GnRH; d 7, $PGF_{2\alpha}$; d 10, GnRH; d 17, GnRH; d 24 and 25, $PGF_{2\alpha}$; and d 27, TAI; Souza et al., 2008) for first postpartum TAI. Primiparous cows started the Double-Ovsynch at 55 and 56 DIM in herds 1 and 2, respectively, and multiparous cows started the Double-Ovsynch at 41 and 42 DIM in herds 1 and 2, respectively. Primiparous cows were scheduled to be inseminated at 82 and 83 DIM instead of 68 and 69 DIM because Stangaferro et al. (2018) demonstrated that the profitability of primiparous

cows is increased when the first insemination is delayed from 60 to 88 DIM. Cows enrolled in the TRM treatment (n = 731) were assigned to first AI protocols according to their early-postpartum estrous characteristics (**EPEC**) as follows (Figure 1):

1. Insemination in estrus: Cows that had at least one intense estrus (heat index ≥70; 0 = minimum, 100 = maximum) detected by the AMD from 10 to 54 and 55 DIM (primiparous; herds 1 and 2, respectively) and from 10 to 40 and 41 DIM (multiparous; herds 1 and 2, respectively) were allowed to be AI upon AMD-detected estrus from 64 to 106 DIM (primiparous) and from 50 to 92 DIM (multiparous). Cows not AI in estrus were submitted to the Double-Ovsynch for TAI; and,

2. Fixed-time AI: Cows that did not have an intense estrus were submitted to the Double-Ovsynch at the same time as the cows in the control treatment and received TAI.

The decision to use heat index ≥70 as the threshold to characterize intense estrus was based on analyses of data from our laboratory (Marques et al., 2020; Chebel and Veronese, 2020; Merenda et al., 2021) in which we identified that cows displaying estrus with HI ≥70 within 45 DIM had greater hazard of pregnancy than cows that were not detected in estrus or had estrus with HI <70 (R. C. Chebel, University of Florida, Gainesville, FL, personal communication).
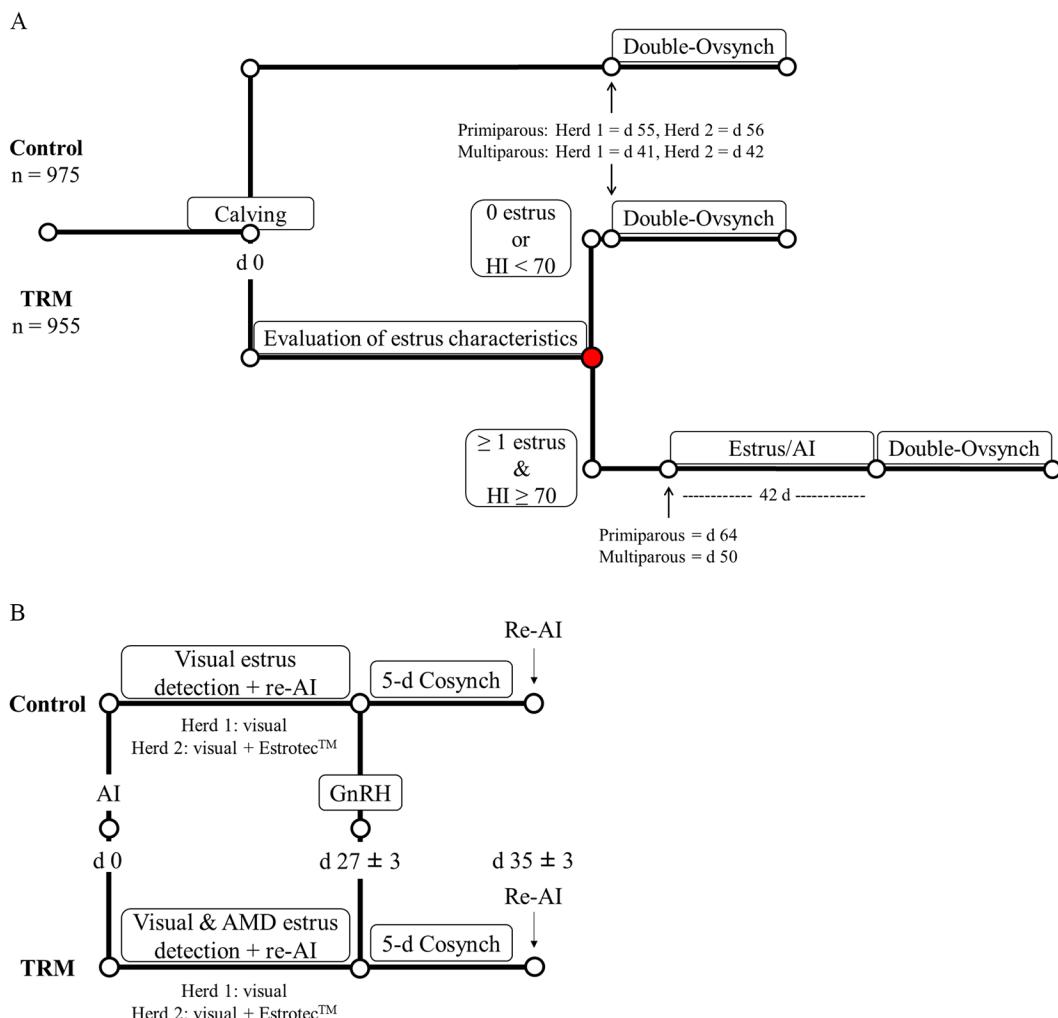
Re-insemination. After the first AI, cows enrolled in the control treatment were re-inseminated when detected in estrus by herd personnel (herd 1: visual detection of signs of estrus; herd 2: visual detection of signs of estrus and activation of Estrotect [Rockway Inc., Spring Valley, WI]). Visual detection of estrus was based on cows standing to be mounted or at least 2 of the following characteristics: mounting other cows, bellowing, increased nervousness and activity, walking fence line, swelling and reddening of the vulva, and vaginal mucous discharge. Cows enrolled in the TRM treatment were re-inseminated when detected in estrus by herd personnel, as described for the control treatment, and upon AMD-detected estrus. Twice daily, 2 and 3 herdspersons in herds 1 and 2, respectively, evaluated cows for estrous behavior as they were brought in for milking, in the holding pen, and as they returned to their pens after milking. In addition, in herd 2, Estrotect was placed on cows 3 d after the first AI and was evaluated at the palpation rails upon exit from the parlor once a day. Estrus was considered to have occurred when ≥50% of the ink had been rubbed off. Estrotect was replaced once it was activated and cows missing an Estrotect received a new one. Herdspersons were allowed to re-inseminate cows detected in estrus by any of the methods described herein. Herdspersons responsible for estrous detection were trained at the start of the experiment by R. C. Chebel. Five days before pregnancy diagnosis, all cows received a GnRH injection (d 0). Cows were examined by transrectal ultrasonography (Easi-Scan; Technology Ltd., Livingston, UK) at 32 ± 3 d after AI for pregnancy diagnosis. Cows diagnosed as nonpregnant concluded the 5-d CO-Synch protocol (d 5 and 6, PGF$_{2\alpha}$; d 8, GnRH and TAI; Santos et al., 2010) and received TAI. Pregnant cows were re-examined 67 ± 3 d after AI.

Semen Use and Timing of Insemination

The selection of sire and type of semen used was based on each of the collaborating herds' management and was based on pedigree (herd 1), genomic traits (herd 2), parity, and service number. Holstein sex-sorted semen and Holstein conventional semen were used for 100% of first postpartum AI of primiparous cows in herds 1 and 2, respectively. Angus conventional semen and Holstein conventional semen were used for 100% of first postpartum AI of multiparous cows in herds 1 and 2, respectively. Among primiparous cows, the distribution of semen type used in the first postpartum AI according to treatment was as follows: control, Holstein conventional = 56.6% and Holstein sex-sorted = 43.4%; TRM, Holstein conventional = 54.6% and Holstein sex-sorted = 45.4%. Among multiparous cows, the distribution of semen type used in the first postpartum AI according to treatment was as follows: control, Holstein conventional = 28.7% and Angus conventional = 71.3%; TRM, Holstein conventional = 27.4% and Angus conventional = 72.6%.

In herd 1, 31.4% and 100% of re-insemination of primiparous and multiparous cows, respectively, were done with Angus conventional semen and the remaining 68.6% of re-inseminations of primiparous cows were done with Holstein sex-sorted semen. In herd 2, 3.5% and 8.4% of re-inseminations of primiparous and multiparous cows, respectively, were done with Angus conventional semen and the remaining re-inseminations were done with Holstein conventional semen. Among primiparous cows, the distribution of semen type used in re-inseminations according to treatment was control – Holstein conventional = 72.3%, Holstein sex-sorted = 18.5%, Angus conventional = 9.2%; TRM – Holstein conventional = 63.4%, Holstein sex-sorted = 25.8%, Angus conventional = 10.8%. Among multiparous cows, the distribution of semen type used in re-inseminations according to treatment was control – Holstein conventional = 35.0% and Angus conventional = 65.0%; TRM – Holstein conventional = 35.6% and Angus conventional = 64.4%.

Figure 1. Design of experiment. First postpartum insemination (A). Control: Double-Ovsynch protocol started at 55 and 56 (primiparous, herds 1 and 2, respectively) and 41 and 42 (multiparous, herds 1 and 2, respectively) DIM for first postpartum insemination at a fixed time. TRM: Cows that had at least one estrus (heat index ≥70; 0 = minimum, 100 = maximum) detected by the AMD by 54 and 55 (primiparous; herds 1 and 2, respectively) and 40 and 41 (multiparous; herds 1 and 2, respectively) DIM were inseminated at AMD-detected estrus starting at 64 (primiparous) and 50 (multiparous) DIM. Cows not inseminated within 42 d were submitted to the Double-Ovsynch protocol and fixed-time insemination. Cows not detected in estrus or with heat index <70 were managed as cows in the control treatment. Re-inseminations (B). Control: Re-insemination at estrus detected by herd personnel (herd 1, visual detection; herd 2, visual detection and activation of Estrotect [Rockway Inc., Spring Valley, WI]). TRM: Re-insemination upon AMD- and herd personnel-detected estrus, as described for the control treatment. Cows not re-inseminated in estrus were enrolled in the 5-d CO-Synch protocol 5 d before pregnancy diagnosis (d 0, GnRH; d 5 and 6, $PGF_{2\alpha}$; d 8, GnRH and TAI). HI = heat index.

In herd 1, 4 technicians inseminated cows 6 d/wk and one relief technician inseminated cows once a week. Four technicians inseminated 80% of the cows and the distribution of technicians across treatments and parity was not different. In herd 2, 7 technicians inseminated cows 6 d/wk and one relief technician inseminated cows once a week. Two technicians inseminated 70% of the cows and the distribution of technicians across treatments and parity was not different.

Cows submitted to the Double-Ovsynch received TAI 16 h after the last GnRH injection, whereas cows submitted to the 5-d CO-Synch received TAI concomitantly with the GnRH injection. Cows in the TRM treatment detected in estrus by the AMD were AI according to the recommendations of the manufacturer (Allflex Livestock Intelligence, Madison, WI). Briefly, the DataFlow2 software identifies cows in estrus based on changes in activity. The onset of estrus occurs once the activity threshold is reached, initiating a "breeding window" (descending from 25 to 0). Independently of semen type, cows were inseminated when the "breeding window" reading was between 20 and 8; thus, cows were inseminated twice daily. Cows detected in estrus based on visual observation or activation of the Estrotect were inseminated immediately.

Reproductive and Productive Outcomes

Cows were followed from enrollment to the start of a new lactation or until they were sold or died. Data regarding AI sire, AI technician, and reproductive outcomes were collected from the on-farm software. For the analysis of hazard of pregnancy, the dates of the AI resulting in a pregnancy carried to term (cows starting a new lactation) and the AI resulting in a pregnancy confirmed at 67 ± 3 d after AI (sold and dead cows) were used. Regardless of occurrence of abortion and inter-AI interval, data from all AI were used. Milk test data were recorded individually at ~30-d intervals. Milk yield, DIM, and milk components (herd 2) were retrieved.

Calculations of Estimated DMI and Live BW

Dry matter intake during the lactation was estimated according to the NRC (2021) using the following formula:

$$DMI \ (kg/d) = [3.7 + (parity \times 5.7) + 0.305 \times MilkE$$
$$(Mcal/d) + 0.022 \times BW \ (kg) + (-0.689 - 1.87 \times parity)$$
$$\times BCS] \times [1 - (0.212 + parity \times 0.136) \times e^{(-0.053 \times DIM)}],$$

where MilkE (milk energy) = $(0.0929 \times \%fat \times yield) + (0.0547 \times \%true \ protein \times yield) + (0.0395 \times \%lactose \times yield)$. In herd 1, milk components data were not available. Thus, to be able to estimate the intake of cows in herd 1, we used the average milk components of herd 2 to estimate the MilkE of cows in herd 1.

Body condition score was assumed to be constant at 3.25 (Ferguson et al., 1994). Dry matter intake during the dry period was estimated to be 1.8 kg/100 kg BW because diet NDF was ~50% (NRC, 2021). Body weight was estimated using the formula (van Arendonk, 1985):

$$BW_{tatitp} = f(age) + f(lactation) + f(pregnancy) =$$
$$A\{1 - [1 - (y_0 A^{-1})^{1/3}]\exp(-kt_a)\}^3$$
$$+ p_l t_l p_2^{-1}\exp(1 - t_l p_2^{-1}) + p_3^3 t_{pc}^3,$$

where f = function, BW_{tatitp} = liveweight of a t_a days old cow at t_l days in lactation, and t_p days pregnant; t_a = age (days); t_l = number of days lactation; t_p = number of days after conception; A = mature liveweight (kg); y_0 = birth weight (kg); k = growth-rate parameter; p_l = maximum decrease of liveweight during the lactation (kg); p_2 = time during the lactation with the minimum liveweight (days); p_3 = pregnancy parameter; and $t_{pc} = t_p - 50$ when $t_p - 50 > 0$; otherwise $t_{pc} = 0$.

According to data from the collaborating herds, mature BW was estimated to be 680 kg and birth BW was estimated to be 40 kg. Growth-rate parameter (k) was assumed to be 0.0028. Maximum decrease of BW during the lactation (p_l) was assumed to be 30 and 50 kg for primiparous and multiparous cows, respectively. Time during the lactation with the minimum BW (p_2) was assumed to be 60 and 80 d for primiparous and multiparous cows, respectively.

Temperature-Humidity Index

Daily weather data were collected from the Valdosta, Georgia (elevation = 226 ft, 30.83°N, 83.28°W; ~50 miles east of herd 1) and Gainesville, Florida (elevation = 187 ft, 29.65°N, 82.33°W; ~45 miles east of herd 2) Weather Underground (https://www.wunderground.com/) laboratories. Using the daily average temperature and humidity, we calculated daily average temperature-humidity index (**THI**). To account for the effect of season, we calculated the number of days within the first 30 d postpartum that cows were exposed to a THI ≥ 68.

Partial Budget Analysis

All calculations were made using an Excel (Microsoft Corp.) spreadsheet. For the purpose of the partial budget analysis, monetary values reported by the collaborating herds during the experiment for each of the variables included in the GP calculation are described in Table 1.

Gross profit was calculated from calving to up to the date the cow was sold, died, or initiated a new lactation as follows:

$$GP = (milk \ income + sale \ value + subsequent \ lactation$$
$$calf \ value) - (feed \ cost + replacement \ cost$$
$$+ fixed \ cost + reproductive \ management \ cost)$$

To assess the economic value of keeping a cow in the herd for an additional lactation compared with replacing her with a primiparous cow based on future profitability, we calculated the retention pay-off (**RPO**; De Vries, 2006; Cabrera, 2012) as follows:

$$RPO = (\{[(value \ of \ replacement \ animal + average$$
$$value \ of \ offspring \ of \ primiparous \ cow) - average \ sale$$
$$value_{LactNum}] \times (maximum \ LactNum - LactNum \ prior$$
$$to \ calving)\}/maximum \ LactNum),$$

and LactNum = lactation number from 0 to 6.

Subsequently, we calculated the adjusted GP to account for the RPO as

$$Adjusted \ GP = GP + RPO.$$

Table 1. Monetary value of variables and labor allocation recorded in the collaborating herds during the experiment and estimated BW at sale according to lactation group

Output	Value	Input	Value
Milk price, $/kg	0.57	Feed cost, $/kg of DM	
Sale value, $/kg live BW	1.60	Lactating cows	0.33
Estimated BW at sale by lactation group, kg		Dry cows	0.29
1	611.28	Fixed cost, $/cow per day	5
2	637.41	Replacement cost, $/cow	1,650
3	661.21	AI	
4	661.22	Supplies, $/AI	0.50
5	661.14	Time, AI/h	30
≥6	663.87	Labor, $/h	25
Calf value, $/calf		Semen cost, $/dose	
Female Holstein	200	Sex-sorted Holstein	18
Male Holstein	25	Holstein	5
Crossbred	180	Beef	5
Primiparous offspring value, $/calf	170	Estrous detection	
		Supplies, $/cow per day	0.05
		Time, cow/h	360
		Labor, $/h	15
		Automated monitoring devices (AMD)	
		Daily fee, $/cow	0.09
		Time to fit/remove AMD, cows/h	30
		Reproductive hormone	
		GnRH, $/dose	1.75
		$PGF_{2\alpha}$, $/dose	1.75
		Supplies, $/dose	0.10
		Time, dose/h	60
		Labor, $/h	15
		Reproductive exams	
		Time, exams/h	30
		Veterinary services, $/h	150

To calculate the estimated sale value of individual cows, we estimated BW on the day of sale using the formula by van Arendonk (1985) described previously. Female Holstein calves born from twin pregnancies with a male calf were considered freemartin and were given the value of a male Holstein calf. The average value of a primiparous cow's offspring was calculated based on the collaborating herds' use of sex-sorted Holstein (80%), conventional Holstein (10%), conventional beef (10%) semen among primiparous animals and the observed stillbirth rate of 7% among primiparous cows. Thus, the average value of a primiparous cow's offspring was estimated to be $170.

Costs associated with reproductive management included cost of reproductive hormones, AI, semen, reproductive tract examinations, and cost of AMD for the TRM treatment and cost of estrous detection for the control treatment. Based on observations carried out during the experiment in the collaborating herds, we estimated that the cost of supplies (e.g., syringes and hypodermic needles) for treatment with reproductive hormones was $0.10/treatment and that 60 cows could be treated per hour. The cost of supplies per AI was $0.50 (sheath, sleeve, semen applicator, water bath) and 30 cows could be AI per hour. We estimated, from discussions with representatives from semen companies (R. C. Chebel, University of Florida, Gainesville, FL, personal communication), the half-life of semen applicators and water

baths to estimate their contributions to the cost of AI supplies. Based on observations of the collaborating herds, we estimated that 360 cows could be evaluated for estrus per hour and the cost of Estrotect was $0.05/cow per day.

Stochastic Analysis

A stochastic Monte Carlo simulation model was developed using (SAS/SAT version 9.4; SAS Institute Inc., Cary, NC) to estimate differences in cash flow between the control and TRM treatments when values for inputs and outputs vary. Fixed inputs were calculated for each treatment to determine differences in GP and adjusted GP between treatments and for each treatment within parity (primiparous vs. multiparous) to determine differences in GP between treatments according to parity. Fixed inputs included average milk production, percentage of cows sold and average BW at sale, percentage of cows starting a new lactation, percentage of cows culled (sold or died), number of live Holstein female and male calves and crossbred calves born, average DMI (lactating + dry periods), average days in the herd (DIM + days dry), number of doses of semen (Holstein and Angus conventional, Holstein sex-sorted), number of AI, number of reproductive tract examinations, and number of treatments with reproductive hormones.

Stochasticity in every iteration of the simulation was introduced for milk price, cow sale price, value of 1-d-old calves (Holstein female and male, crossbred), feed cost, fixed cost, replacement cost, semen cost, labor cost (AI, estrous detection, reproductive tract examination, reproductive hormone treatment, fitting AMD), and daily cost of AMD. Historical (January 2012 to October 2021) prices of milk, cow sales, and replacement cost (Quick Stats; National Agricultural Statistics Service, 2024a) and feed cost (Economic Research Service, 2024) were retrieved from USDA electronic databases. Labor cost for performing estrous detection, hormonal treatments, fitting collars, and AI were gathered from USDA (Economic Research Service, 2024; National Agricultural Statistics Service, 2024b) and from the collaborating herds and 10 other dairies form across Florida and Georgia (R. C. Chebel, University of Florida, Gainesville, FL, personal communication). Semen cost was based on what was reported by the collaborating herds and 10 other dairies from across Florida and Georgia (R. C. Chebel, University of Florida, Gainesville, FL, personal communication).

Simulations were run and recorded for 100,000 iterations. For each iteration, the GP was calculated for each treatment and parity as

$$GP = [(yield \times milk\ price) + (\%\ cows\ sold$$
$$\times estimated\ BW \times cow\ sale\ value) + (Holstein\ female$$
$$calves \times calf\ value) + (Holstein\ male\ calves$$
$$\times calf\ value) + (crossbred\ calves \times calf\ value)]$$
$$- [(DMI \times lactating\ cow\ feed\ cost) + (DMI \times dry\ cow$$
$$feed\ cost) + (days\ in\ the\ herd \times fixed\ cost) + (\%\ cows$$
$$replaced \times replacement\ cost) + (sex\text{-}sorted\ Holstein$$
$$semen\ doses \times semen\ cost) + (Holstein\ semen\ doses$$
$$\times semen\ cost) + (Angus\ semen\ doses \times semen\ cost)$$
$$+ (number\ of\ AI \times cost\ of\ AI\ supplies) + (number\ of\ AI$$
$$\times labor\ cost) + (reproductive\ examinations \times labor\ cost)$$
$$+ (reproductive\ hormone\ treatments \times cost\ of\ supplies)$$
$$+ (reproductive\ hormone\ treatments \times labor\ cost)].$$

To account for the differences in reproductive management between treatments, we added to the costs:

$$TRM = [(2 \times labor\ cost\ to\ fit/remove\ AMD)$$
$$+ (days\ with\ AMD \times daily\ cost\ of\ AMD)];$$

$$CON = [(DIM \times cost\ of\ estrous\ detection\ supplies)$$
$$+ (DIM \times estrous\ detection\ labor\ cost)].$$

Adjusted GP was calculated as follows:

$$Adjusted\ GP = GP + (\%\ cows_{LactNum} \times \%\ cows\ replaced$$
$$\times RPO) + (\%\ cows_{LactNum} \times \%\ cows\ retained \times RPO).$$

Statistical Analyses

A total of 1,480 cows were used for statistical analyses because 18 cows were diagnosed as nonpregnant before calving, 132 cows were deemed not eligible for AI by the herds' managers, 169 cows were removed from the herd, 73 cows had damaged straps, 7 cows had defective AMD, and 51 cows did not follow the assigned treatment. We carried out post hoc sample calculations using Medcalc (Ostend, Belgium). To detect a $215/lactation (control = $4,000 vs. TRM = $4,215) difference in GP, 696 cows/treatment would protect against type I ($\alpha = 0.05$) and type II ($\beta = 0.20$) errors when the SD of GP is $1,430.

All statistics analyses were carried out in SAS (SAS/SAT version 9.4; SAS Institute Inc., Cary, NC). Binary outcomes (e.g., percentages of cows starting a new lactation) were analyzed by logistic regression (LOGISTIC procedure). Continuous outcomes with normally distributed residuals (estimated BW at sale, DIM, lactation total milk yield and estimated DMI, monthly milk yield up to 305 DIM, gestation length, days dry and estimated DMI during the dry period, calving interval, milk revenue, feeding cost during the lactation, fixed cost, reproductive management cost, and GP) were analyzed by ANOVA (MIXED procedure). Ordinal outcomes (e.g., numbers of AI, treatments with reproductive hormones, and reproductive examinations, and number of live calves produced in the subsequent lactation) were analyzed by negative binomial regression (GENMOD procedure). All models included treatment, parity, treatment × parity interaction, dairy, treatment × dairy interaction, and number of days within the first 30 d postpartum with THI $\geq$ 68 (linear and quadratic). When variables were measured repeatedly (e.g., monthly milk yield), we included in the models the fixed effects of time (e.g., month of lactation) and the interactions between treatment × time, parity × time, and treatment × parity × time. Continuous variables that had residuals that were not normally distributed (e.g., cow sales, residual cow value, calf value, lactating cow feed cost, dry cow feed cost, and replacement cost) were analyzed by Kruskal-Wallis (NPAR1WAY procedure). In such cases, the univariable fixed effects were treatment or parity.

Differences were declared when $P \leq 0.05$ and tendencies were declared when $0.05 < P \leq 0.10$.

RESULTS

Gonzalez et al. (2023) reported results regarding P/AI (first AI and re-insemination) and hazard of pregnancy from calving to 305 d postpartum.

Descriptive Statistics

The percentage of primiparous cows (control = 37.3%, TRM = 35.6%) and the number of lactations (control = 2.2 ± 0.1, TRM = 2.2 ± 0.1) were not ($P \geq 0.65$) different between treatments. Treatments did not ($P \geq 0.16$) differ regarding genomic breeding values for milk yield (control = 826.0 ± 47.3 kg, TRM = 872.8 ± 47.8 kg) and net merit (control = $518.5 ± $13.0, TRM = $493.62 ± $13.1), age at first calving (control = 23.4 ± 0.1 mo, TRM = 23.5 ± 0.1 mo), 305-d mature equivalent milk yield during the lactation of enrollment (control = 13,938 ± 87.1 kg, TRM = 14,101 ± 87.7 kg), gestation length (control = 275.4 ± 0.2 d, TRM = 275.2 ± 0.2 d), and days dry during the lactation of enrollment (control = 53.8 ± 0.7 d, TRM = 54.1 ± 0.7 d).

Cows in the TRM treatment were ($P = 0.05$) less likely to have clinical mastitis within 60 DIM (control = 3.5% ± 0.7%, TRM = 2.1% ± 0.5%), but we did not ($P \geq 0.22$) detect differences between treatments regarding the percentage of cows with male offspring (control = 36.3% ± 1.9%, TRM = 36.6% ± 1.9%), calving problems (control = 21.0% ± 1.6%, TRM = 20.4% ± 1.6%), uterine diseases (control = 16.3% ± 1.4%, TRM = 14.0% ± 1.3%), metabolic diseases within 60 DIM (control = 3.3% ± 0.8%, TRM = 2.4% ± 0.6%), digestive disorders within 60 DIM (control = 3.6% ± 0.7%, TRM = 4.1% ± 0.7%), and lameness within 60 DIM (control = 4.1% ± 0.8%, TRM = 3.1% ± 0.7%).

Overall, 50.9% of cows had an intense estrus postpartum and treatment was not ($P = 0.83$) associated with it (control = 50.6%, TRM = 51.2%). Primiparous cows were ($P < 0.01$) more likely than multiparous cows to have an intense estrus postpartum (58.1% vs. 46.8%). Cows in herd 1 tended ($P = 0.09$) to be more likely to have an intense estrus postpartum than cows in herd 2 (52.3% vs. 48.5%).

Lactation Performance

The hazard of pregnancy was ($P < 0.01$) greater for the TRM treatment, independent of parity (Table 2). Consequently, cows in the TRM treatment were ($P < 0.01$) more likely to start a new lactation, whereas cows in the control treatment were ($P = 0.02$) more likely to be sold.

The estimated BW at sale was not ($P = 0.68$) different between treatments (Table 2) because the interval from calving to sale was not ($P = 0.51$) affected by treatment (TRM = 344.0 ± 13.8 d, control = 354.5 ± 12.3 d). Days in milk was not ($P \geq 0.54$) affected by treatment among cows that started a new lactation, cows dead in the herd, and cows sold. Milk yield up to 305 DIM was ($P = 0.03$) greater for cows in the TRM treatment (41.4 ± 0.2 kg/d vs. 40.8 ± 0.2 kg/d). Conversely, total lactation milk yield ($P \geq 0.26$) and estimated DMI during the lactation ($P \geq 0.42$) were not affected by treatment, independent of disposition of the cow at the end of the lactation.

Treatment had no ($P \geq 0.72$) effect on number of AI and reproductive examinations during the lactation, but cows in the TRM treatment received fewer ($P < 0.01$) treatments with exogenous reproductive hormones. Among cows starting a new lactation, treatments did not ($P \geq 0.25$) differ regarding interval from calving to pregnancy, gestation length at dry-off, dry period length, dry period estimated intake, calving interval, and number of live calves produced.

Economic Outcomes

In Table 3 we depicted the effects of treatments on economic outcomes. Treatment did not ($P \geq 0.26$) affect milk revenue, but the TRM treatment resulted in a $55/cow reduction in income from cow sales ($P < 0.01$) and tended ($P = 0.08$) to increase calf value by approximately $10/cow. Cost of feeding lactating and dry cows, fixed cost, and cost of reproductive management were not ($P \geq 0.44$) affected by treatment. Conversely, the TRM treatment reduced ($P < 0.01$) the replacement cost by approximately $80/cow. Although IOFC was not ($P = 0.24$) affected by treatment, GP tended ($P = 0.08$) to be $108/cow greater for cows in the TRM treatment. When we accounted for RPO, however, the adjusted GP was not ($P = 0.16$) affected by treatment.

Stochastic Model Results

The monetary values of variables used in the Monte Carlo stochastic analyses of economic return are depicted in Table 4. The cost of supplies for treatment with exogenous hormones and insemination were kept constant at $0.10/dose and $0.50/insemination. The mean (±SD) difference in GP was $87.8 ± $12.6/cow in favor of the TRM treatment and 95% of the scenarios ranged from $67.2/cow to $108.5/cow (minimum = $30.2/cow, maximum = $141.1/cow; Figure 2A). The variables with the highest and lowest Pearson correlation coefficient with GP difference between treatments were replacement cost (r = 0.78), milk price (r = 0.33), cost of estrous detection (r = 0.15), feed cost of dry cows (r = −0.12),

Table 2. Effects of treatments on lactational and reproductive performances according to parity

Item	Primiparous		Multiparous		P-value[3]		
	Control[1] (n = 279)	TRM[2] (n = 260)	Control[1] (n = 470)	TRM[2] (n = 471)	TRT	Parity	TRT × parity
Cows starting a new lactation, %	87.8	90.8	70.9	78.1	<0.01	<0.01	0.90
Cows dead in the herd, %	1.1	0.8	2.6	2.6	0.87	0.04	0.74
Cows sold, %	11.1	8.5	26.6	19.3	0.02	<0.01	0.91
Estimated BW at sale, kg (±SEM)	611.2 ± 5.1	611.9 ± 6.2	657.2 ± 3.1	658.1 ± 3.5	0.68	<0.01	0.99
DIM (±SEM)							
Cows starting a new lactation	351.1 ± 3.6	351.7 ± 3.6	318.5 ± 2.8	319.9 ± 2.8	0.66	<0.01	0.89
Cows dead in the herd	290.6 ± 79.3	280.8 ± 87.5	225.0 ± 27.2	218.2 ± 23.8	0.54	0.32	0.99
Cows sold	339.2 ± 26.1	322.0 ± 29.8	293.0 ± 13.8	272.3 ± 14.1	0.56	0.01	0.88
Lactation milk yield, kg (±SEM)							
Cows starting a new lactation	12,728.5 ± 170.3	12,838.5 ± 172.8	13,681.5 ± 158.6	13,899.4 ± 157.2	0.26	<0.01	0.77
Cows dead in the herd	11,180.2 ± 2,522.3	9,367.5 ± 2,296.9	10,561.8 ± 1,067.8	10,558.6 ± 982.9	0.81	0.85	0.67
Sold cows	11,331.0 ± 912.8	10,865.0 ± 1,051.3	12,409.3 ± 610.7	11,949.0 ± 647.9	0.87	0.22	0.98
Lactation estimated intake, kg (±SEM)							
Cows starting a new lactation	7,621.3 ± 86.1	7,654.1 ± 87.0	7,614.4 ± 74.5	7,680.2 ± 73.4	0.42	0.90	0.84
Cows dead in the herd	6,390.7 ± 1,699.9	6,013.1 ± 1,827.4	5,482.4 ± 646.9	5,435.5 ± 577.3	0.66	0.57	0.91
Sold cows	7,082.6 ± 568.6	6,748.0 ± 650.6	6,950.0 ± 340.8	6,546. ± 353.7	0.79	0.74	0.94
All cows							
AI (±SEM)	3.0 ± 0.1	3.1 ± 0.1	2.8 ± 0.1	2.6 ± 0.1	0.72	<0.01	0.30
Reproductive hormone treatments (±SEM)	10.2 ± 0.3	4.2 ± 0.2	10.0 ± 0.3	4.6 ± 0.1	<0.01	0.47	0.12
Reproductive examinations (±SEM)	2.7 ± 0.1	2.8 ± 0.1	2.6 ± 0.1	2.5 ± 0.1	0.75	0.04	0.30
Adjusted hazard of pregnancy (95% CI)	Ref.[4]	1.07 (0.89, 1.28)	Ref.	1.25 (1.08, 1.45)	<0.01	0.92	0.18
Cows deemed not eligible for AI, %	5.4	3.5	12.3	8.9	0.03	0.02	0.64
Cows starting a new lactation							
Interval from calving to pregnancy, d (±SEM)	123.0 ± 3.4	124.6 ± 3.5	97.2 ± 2.3	97.0 ± 2.3	0.87	<0.01	0.77
Gestation length at dry-off, d (±SEM)	220.5 ± 1.0	220.8 ± 1.0	214.9 ± 0.9	215.4 ± 0.9	0.65	<0.01	0.96
Dry period length, d (±SEM)	54.1 ± 1.1	54.1 ± 1.1	61.4 ± 0.9	60.1 ± 0.9	0.42	<0.01	0.54
Dry period estimated intake, kg (±SEM)	630.6 ± 12.4	630.6 ± 12.5	755.0 ± 10.6	739.7 ± 10.2	0.41	<0.01	0.50
Calving interval, d (±SEM)	406.4 ± 3.6	407.1 ± 3.6	380.7 ± 2.9	380.7 ± 2.9	0.96	<0.01	0.93
Number of live calves	1.02 ± 0.07	1.00 ± 0.07	1.05 ± 0.06	1.06 ± 0.05	0.25	0.02	0.84

[1]Control = Double-Ovsynch protocol started at 55 and 56 (primiparous, herds 1 and 2, respectively) and 41 and 42 (multiparous, herds 1 and 2, respectively) DIM for first postpartum insemination at a fixed time. Re-insemination at estrus detected by herd personnel (herd 1, visual detection; herd 2, visual detection and activation of Estrotect [Rockway Inc., Spring Valley, WI]).

[2]TRM = Cows that had at least one estrus (heat index ≥70; 0 = minimum, 100 = maximum) detected by the AMD by 54 and 55 (primiparous; herds 1 and 2, respectively) and 40 and 41 (multiparous; herds 1 and 2, respectively) DIM were inseminated at AMD-detected estrus starting at 64 (primiparous) and 50 (multiparous) DIM. Cows not inseminated within 42 d were submitted to the Double-Ovsynch protocol and fixed-time insemination. Cows not detected in estrus or with heat index <70 were managed as cows in the control treatment. Re-insemination upon AMD- and herd personnel-detected estrus, as described for the control treatment.

[3]TRT = treatment.

[4]Ref. = referent.

Table 3. Effects of treatments on economic outcomes and GP according to parity

	Primiparous		Multiparous		P-value		
	Control[1]	TRM[2]	Control[1]	TRM[2]	TRT	Parity	TRT × parity
Outputs							
Milk revenue, $/cow	7,514.3 ± 122.5	7,556.3 ± 126.0	7,836.7 ± 98.4	7,943.1 ± 99.3	0.34	<0.01	0.75
Cow sales,[3] $/cow	108.5	82.7	277.4	202.1	<0.01	<0.01	NA
Calf value,[3] $/cow	122.9	128.1	117.7	129.8	0.08	<0.01	NA
Inputs							
Lactating cow feed cost, $/cow	2,553.6 ± 37.8	2,555.3 ± 38.8	2,481.9 ± 30.3	2,488.7 ± 30.5	0.72	0.08	0.94
Dry cow feed cost, $/cow	185.6 ± 3.7	184.7 ± 3.8	221.6 ± 3.2	217.9 ± 3.1	0.44	<0.01	0.68
Replacement cost,[3] $/cow	198.0	150.0	473.5	355.3	<0.01	<0.01	NA
Fixed cost, $/cow	2,033.3 ± 25.5	2,038.0 ± 26.4	1,814.5 ± 20.8	1,826.2 ± 21.0	0.52	<0.01	0.88
Reproductive management cost, $/cow	85.5 ± 1.9	87.4 ± 2.0	68.7 ± 1.2	66.3 ± 1.1	0.44	<0.01	0.14
Income over feed cost, $/cow	4,961.3 ± 87.2	5,000.4 ± 89.7	5,354.4 ± 70.0	5,454.7 ± 70.7	0.24	<0.01	0.70
Gross profit,[4] $/cow	2,698.1 ± 73.4	2,761.8 ± 75.5	3,223.1 ± 58.9	3,345.4 ± 59.3	0.08	<0.01	0.67
Retention pay-off,[3,5] $/cow	719.6	715.4	536.9	505.4	<0.01	<0.01	NA
Adjusted gross profit,[6] $/cow	3,423.5 ± 72.0	3,479.6 ± 74.1	3,748.8 ± 57.8	3,843.9 ± 58.3	0.16	<0.01	0.75

[1]Control = Double-Ovsynch protocol started at 55 and 56 (primiparous, herds 1 and 2, respectively) and 41 and 42 (multiparous, herds 1 and 2, respectively) DIM for first postpartum insemination at a fixed time. Re-insemination at estrus detected by herd personnel (herd 1, visual detection; herd 2, visual detection and activation of Estrotect [Rockway Inc., Spring Valley, WI]).

[2]TRM = Cows that had at least one estrus (heat index ≥70; 0 = minimum, 100 = maximum) detected by the AMD by 54 and 55 (primiparous; herds 1 and 2, respectively) and 40 and 41 (multiparous; herds 1 and 2, respectively) DIM were inseminated at AMD-detected estrus starting at 64 (primiparous) and 50 (multiparous) DIM. Cows not inseminated within 42 d were submitted to the Double-Ovsynch protocol and fixed-time insemination. Cows not detected in estrus or with heat index <70 were managed as cows in the control treatment. Re-insemination upon AMD- and herd personnel-detected estrus, as described for the control treatment.

[3]Results referent to nonparametric analysis (Kruskal-Wallis).

[4]Gross profit = (milk income + sale value + subsequent lactation calf value) − (feed cost + replacement cost + fixed cost + reproductive management cost).

[5]Retention pay-off = ({[(value of replacement animal + average value of offspring of primiparous cow) − average sale valueLactNum] × (maximum LactNum − LactNum prior to calving)}/maximum LactNum), where LactNum = lactation number from 0 to 6.

[6]Adjusted gross profit = (milk income + sale value + subsequent lactation calf value + RPO) − (feed cost + replacement cost + fixed cost + reproductive management cost).

Table 4. Monetary value of variables used in the Monte Carlo stochastic analyses of economic return

Outputs ± SD (dist.: min., max.)[1]		Inputs ± SD (dist.: min., max.)[1]	
Milk price,[2] $/kg	0.50 ± 0.03 (N: 0.37, 0.63)	Rearing cost,[3] $/heifer	1,485 ± 181 (N: 724, 2,247)
Cow sale value,[3] $/kg of live BW	1.65 ± 0.12 (N: 1.15, 2.17)	Feed cost,[4] $/kg of DM	
Calf value,[3] $/calf		Lactating	0.30 ± 0.04 (N: 0.14, 0.47)
Female Holstein	200.1 ± 39.9 (N: 8.8, 357)	Dry	0.25 ± 0.04 (N: 0.07, 0.41)
Male Holstein	25.0 ± 5.0 (N: 3.3, 47.3)	Fixed cost, $/cow per day	5.0 ± 0.3 (N: 3.9, 6.1)
Crossbred	180 ± 34.9 (N: 27.7, 315.6)	Replacement cost,[3] $/heifer	1,485 ± 181 (N: 724, 2,247)
Primiparous offspring value, $/calf	170 ± 35 (N: 25.8, 327.8)	Semen,[5] $/dose	
		Sex-sorted Holstein	18 ± 3 (N: 4.2, 30.5)
		Holstein	5.0 ± 0.5 (N: 3.0, 7.0)
		Beef	5.0 ± 0.5 (N: 2.9, 7.1)
		Reproductive hormones,[6] $/dose	1.8 ± 0.2 (N: 0.7, 2.9)
		AMD cost,[7] $/cow per day	0.09 ± 0.01 (N: 0.04, 0.13)
		Labor cost[8]	
		Insemination, $/AI	0.83 ± 0.12 (U: 0.63, 1.04)
		Estrous detection, $/cow per day	0.04 ± 0.01 (U: 0.03, 0.05)
		Reproductive hormone, $/treatment	0.25 ± 0.03 (U: 0.19, 0.31)
		AMD fitting/removing, $/h	0.50 ± 0.07 (U: 0.38, 0.62)
		Reproductive exams, $/exam	3.0 ± 0.6 (U: 2.0, 4.0)

[1]Dist. = distribution (N = normal, U = uniform), min. = minimum, max. = maximum.
[2]Source: Quick Stats, National Agricultural Statistics Services (2024a).
[3]Source: Historical Cattle Prices (Schulz, 2020).
[4]Source: Economic Research Service (2024).
[5]Source: Olynk and Wolf (2007), and confirmed with 5 commercial herds in north-central Florida and south-central Georgia.
[6]Market price from Southeast Milk Inc. (Belleview, FL).
[7]Market price from Merck Animal Health (Rahway, NJ); AMD = automatic monitoring device.
[8]Source: National Agricultural Statistics Service (2022).
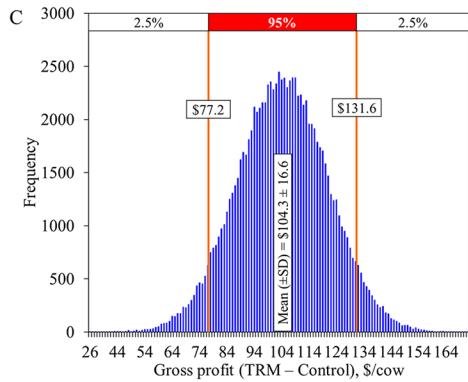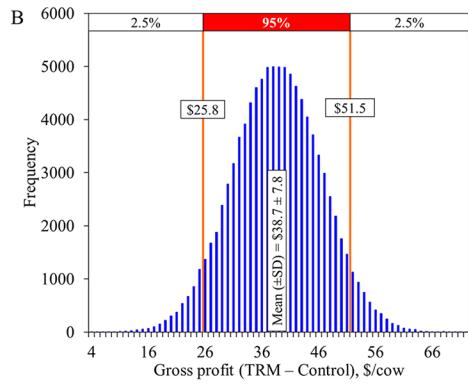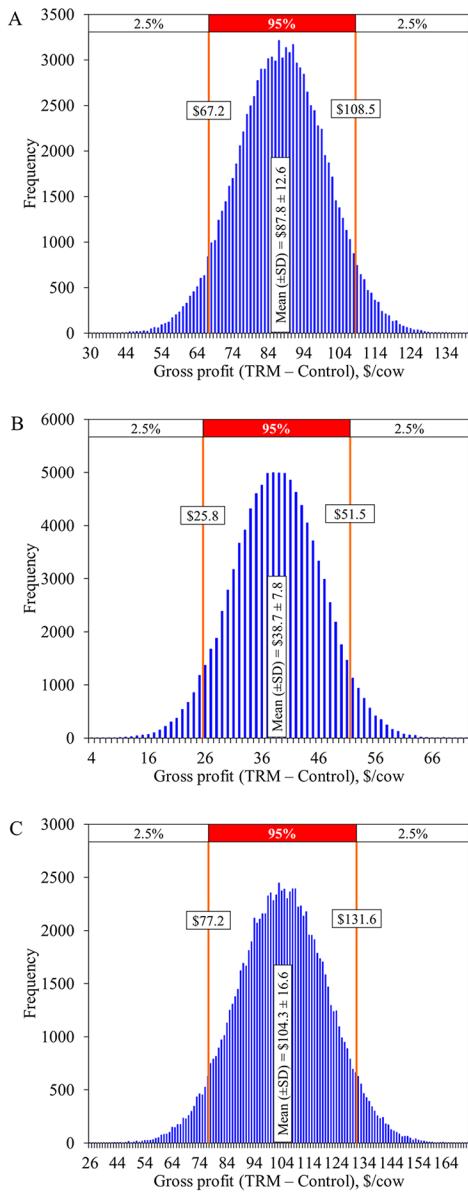
cost of AMD (r = −0.32), and cow sale value (r = −0.33). Among primiparous cows, the mean (±SD) difference in GP between the TRM and control treatments was $38.7 ± $7.8/cow (minimum = $4.4/cow, maximum = $77.2/cow; Figure 2B), and in 95% of the scenarios the difference in GP ranged between $25.8/cow and $51.5/cow. Among multiparous cows, the mean (±SD) GP difference between the TRM and control treatments was $104.3 ± $16.6/cow, with 95% of the scenarios ranging from $77.2/cow to $131.6/cow (minimum = $26.0/cow, maximum = $172.5/cow; Figure 2C).

According to the stochastic model, the mean (±SD) difference in adjusted GP was $68.3 ± $8.7/cow in favor of the TRM treatment, with 95% of the scenarios ranging from $54.1/cow to $82.6/cow (minimum = $26.0/cow, maximum = $103.8/cow; Figure 3A). The variables with the highest and lowest Pearson correlation coefficient with adjusted GP difference between treatments were replacement cost (r = 0.57), milk price (r = 0.48), cost of estrous detection (r = 0.22), feed cost of dry cows (r = −0.18), cow sale value (r = −0.26), and cost of AMD (r = −0.47; Table 5). Among primiparous cows, the mean (±SD) difference in GP between the TRM and control treatments was $35.5 ± $7.2/cow (minimum = $4.7/cow, maximum = $70.8/cow; Figure 3B), and in 95% of the scenarios the difference in GP ranged between $23.7/cow and $47.2/cow. Among multiparous cows, the mean (±SD) GP difference between the TRM and control treat-

ments was $79.6 ± $11.3/cow, with 95% of the scenarios ranging from $61.0/cow to $98.3/cow (minimum = $21.4/cow, maximum = $126.9/cow; Figure 3C). In Figure 4, we depicted tornado graphs showing the contribution of each variable to the differences in adjusted GP between cows in the TRM and control treatments for the 100,000 iterations of stochastic simulation.
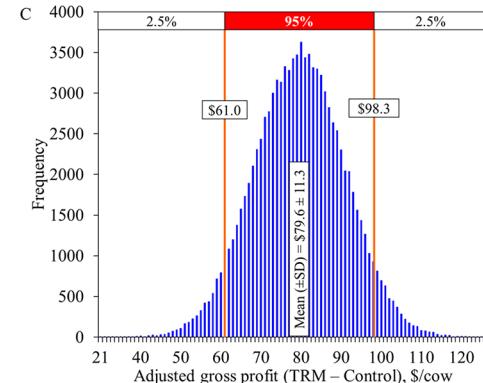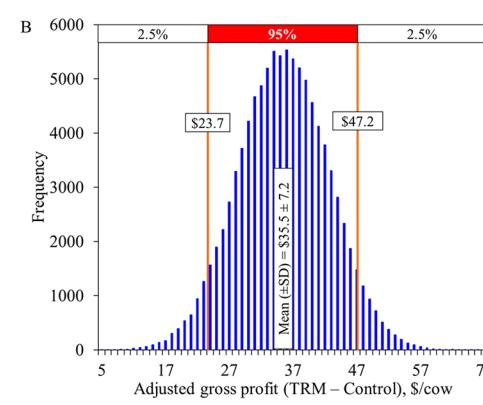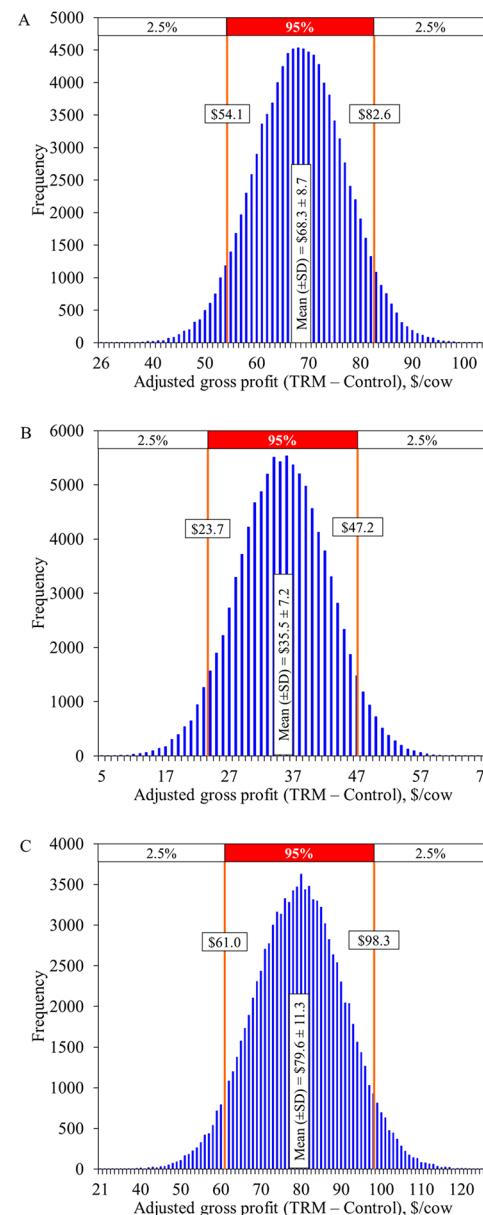
DISCUSSION

Efficient reproductive management is vital for the economic success of dairy operations because it affects milk production efficiency (e.g., IOFC), longevity, availability of replacement animals, and culling policies. In the current experiment, we evaluated the economic performance of lactating Holstein cows from 2 herds located in north-central Florida subjected to different reproductive management strategies for the entire lactation. The TRM treatment relied primarily on the use of an AMD. For first AI, cows were subjected to an OvSP + TAI or were left untreated according to EPEC, whereas re-insemination of nonpregnant cows occurred at AMD-detected estrus. The control treatment, conversely, relied heavily on exogenous reproductive hormones as all cows were subjected to the Double-Ovsynch for first AI and were mostly re-inseminated at a fixed time following an OvSP. As expected, the TRM treatment produced a significant decrease in use of reproductive hormones (4.5 ±

Figure 2. Relative frequency distribution for differences in gross profit between cows in the TRM and control treatments, (A) overall, (B) primiparous, and (C) multiparous, for 100,000 iterations of stochastic simulation. Control: Double-Ovsynch protocol started at 55 and 56 (primiparous, herds 1 and 2, respectively) and 41 and 42 (multiparous, herds 1 and 2, respectively) DIM for first postpartum insemination at a fixed time. Re-insemination at estrus detected by herd personnel (herd 1, visual detection; herd 2, visual detection and activation of Estrotect [Rockway Inc., Spring Valley, WI]). TRM: Cows that had at least one estrus (heat index ≥70; 0 = minimum, 100 = maximum) detected by the AMD by 54 and 55 (primiparous; herds 1 and 2, respectively) and 40 and 41 (multiparous; herds 1 and 2, respectively) DIM were inseminated at AMD-detected estrus starting at 64 (primiparous) and 50 (multiparous) DIM. Cows not inseminated within 42 d were submitted to the Double-Ovsynch protocol and fixed-time insemination. Cows not detected in estrus or with a heat index <70 were managed as cows in the control treatment. TRM: Re-insemination upon AMD- and herd personnel-detected estrus, as described for the control treatment. Cows not re-inseminated in estrus were enrolled in the 5-d CO-Synch protocol 5 d before pregnancy diagnosis (d 0, GnRH; d 5 and 6, PGF$_{2\alpha}$; d 8, GnRH and TAI).

Figure 3. Relative frequency distribution for differences in adjusted gross profit between cows in the TRM and control treatments, (A) overall, (B) primiparous, and (C) multiparous, for 100,000 iterations of stochastic simulation. Control: Double-Ovsynch protocol started at 55 and 56 (primiparous, herds 1 and 2, respectively) and 41 and 42 (multiparous, herds 1 and 2, respectively) DIM for first postpartum insemination at a fixed time. Re-insemination at estrus detected by herd personnel (herd 1, visual detection; herd 2, visual detection and activation of Estrotect [Rockway Inc., Spring Valley, WI]). TRM: Cows that had at least one estrus (heat index ≥70; 0 = minimum, 100 = maximum) detected by the AMD by 54 and 55 (primiparous; herds 1 and 2, respectively) and 40 and 41 (multiparous; herds 1 and 2, respectively) DIM were inseminated at AMD-detected estrus starting at 64 (primiparous) and 50 (multiparous) DIM. Cows not inseminated within 42 d were submitted to the Double-Ovsynch protocol and fixed-time insemination. Cows not detected in estrus or with heat index <70 were managed as cows in the control treatment. TRM: Re-insemination upon AMD- and herd personnel-detected estrus, as described for the control treatment. Cows not re-inseminated in estrus were enrolled in the 5-d CO-Synch protocol 5 d before pregnancy diagnosis (d 0, GnRH; d 5 and 6, PGF$_{2\alpha}$; d 8, GnRH and TAI).

Table 5. Pearson correlation coefficients between monetary values of variables used in the Monte Carlo stochastic analyses and adjusted GP difference between the TRM[1] and control[2] treatments according to 100,000 iterations

Item	Variable	Overall		Primiparous		Multiparous	
		r	P-value	r	P-value	r	P-value
Outputs	Milk price	0.477	<0.0001	0.101	<0.0001	0.527	<0.0001
	Sale price	−0.261	<0.0001	−0.225	<0.0001	−0.290	<0.0001
	HO[3] female calf value	−0.009	0.006	0.167	<0.0001	−0.035	<0.0001
	HO male calf value	−0.006	0.074	−0.015	<0.0001	0.0001	0.966
	Crossbred calf value	0.212	<0.0001	−0.022	<0.0001	0.226	<0.0001
	Primiparous offspring value	−0.112	<0.0001	−0.026	<0.0001	−0.110	<0.0001
Inputs	Lactating cow feed cost	−0.015	<0.0001	0.121	<0.0001	−0.106	<0.0001
	Dry cow feed cost	−0.180	<0.0001	−0.088	<0.0001	−0.183	<0.0001
	Replacement cost	0.572	<0.0001	0.626	<0.0001	0.609	<0.0001
	Fixed cost	−0.035	<0.0001	0.015	<0.0001	−0.079	<0.0001
Reproductive management	HO sex-sorted semen cost	−0.020	<0.0001	−0.080	<0.0001	−0.001	0.764
	HO conventional semen cost	0.010	0.001	0.011	0.0003	0.008	0.014
	Beef semen cost	0.003	0.422	0.0008	0.796	0.005	0.102
	Reproductive hormone cost	0.136	<0.0001	0.175	<0.0001	0.101	<0.0001
	AMD cost	−0.468	<0.0001	−0.613	<0.0001	−0.342	<0.0001
	Artificial insemination labor cost	0.003	0.411	0.002	0.557	0.003	0.365
	Estrous detection labor cost	0.222	<0.0001	0.293	<0.0001	0.161	<0.0001
	Reproductive hormone labor cost	0.021	<0.0001	0.029	<0.0001	0.016	<0.0001
	AMD fitting labor cost	0.0004	0.891	−0.001	0.729	0.001	0.769
	Reproductive exam labor cost	0.001	0.652	−0.010	0.002	0.005	0.128

[1]Control: Cows subjected to the Double-Ovsynch protocol (Souza et al., 2008) at 55 and 56 DIM (primiparous, herds 1 and 2, respectively) and 41 and 42 DIM (multiparous, herds 1 and 2, respectively) for first postpartum AI at a fixed time. Cows re-inseminated when detected in estrus by herd personnel (herd 1, visual detection of signs of estrus; herd 2, visual detection of signs of estrus and activation of Estrotect [Rockway Inc., Spring Valley, WI]).
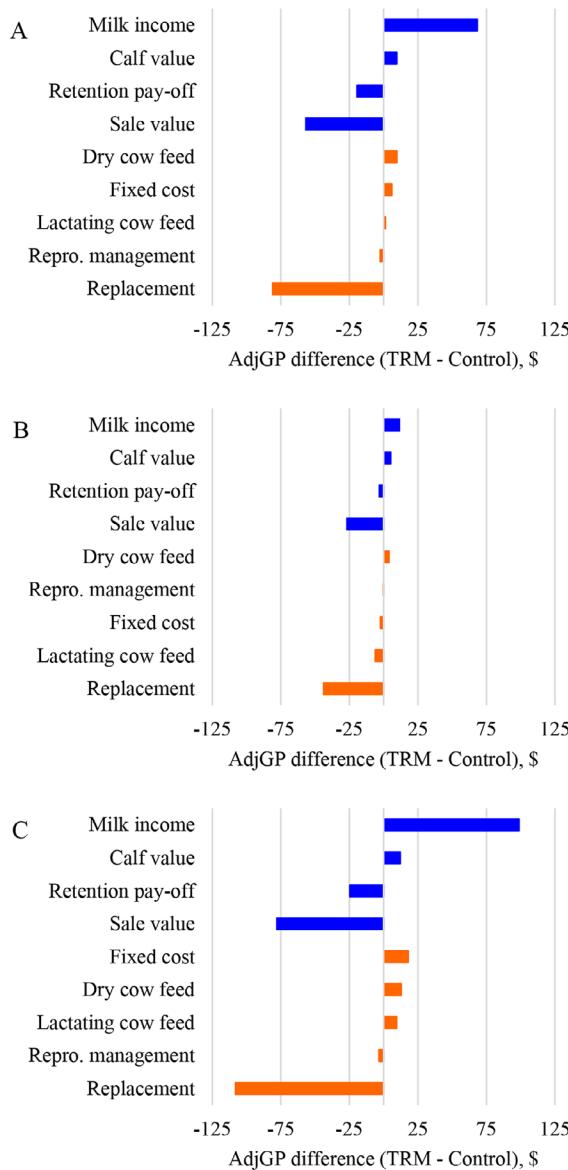
[2]TRM: Cows that had at least one estrus detected by the automated device with heat index ≥70 (0 = minimum, 100 = maximum) by 54 and 55 DIM (primiparous; herds 1 and 2, respectively) and 40 and 41 DIM (multiparous; herds 1 and 2, respectively) were inseminated upon automated device-detected estrus starting at 64 DIM (primiparous) and 50 DIM (multiparous). Cows not inseminated within 42 d were submitted to the Double-Ovsynch protocol (Souza et al., 2008) and fixed-time insemination. Cows that were not detected in estrus or had a heat index <70 were subjected to the Double-Ovsynch protocol and fixed-time insemination as in the control treatment. Cows were re-inseminated upon detection of estrus by herd personnel, as described for the control treatment, and automated device.

[3]HO = Holstein.

0.1 vs. 10.1 ± 0.2 doses/cow). In Gonzalez et al. (2023), we reported the effects of treatment and the interaction between treatment and genomic estimated breeding values for daughter pregnancy rates on risk of pregnancy following the first AI and re-insemination. It is worth noting that in Gonzalez et al. (2023) the "follow-up period" for reproductive performance of pregnant cows ended when pregnancy was confirmed at 67 d after AI and all cows were followed until they completed 305 DIM or until they were sold or died. In the current experiment, we followed the cows from enrollment to the onset of a new lactation or until cows died or were sold. Thus, small discrepancies may exist regarding number of AI and treatments with reproductive hormones between the 2 reports.

In the conditions of the current experiment, the TRM treatment had a positive effect on the hazard of pregnancy, regardless of parity and despite the fact that the risk of pregnancy to first AI of primiparous cows in the TRM treatment was lower than that of the control treatment (Gonzalez et al., 2023). The advantage of the TRM treatment regarding hazard of pregnancy through-

out the lactation, therefore, was explained by the faster re-insemination of nonpregnant cows, because the risk of pregnancy after re-insemination was not different between treatments (Gonzalez et al., 2023). These results indicate that, in the conditions of the collaborating herds, the use of AMD for re-insemination of nonpregnant cows had a greater influence on the difference between the TRM and control treatments than the different strategies used for first postpartum AI. Marques et al. (2020) had demonstrated that the hazard of re-insemination was improved by the use of AMD compared with visual detection of estrus aided by an estrus patch in one of the collaborating herds. Detecting estrus of modern lactating Holstein cows by visual means is challenging. Smaller circulating concentrations of estradiol, in part, as a result of their elevated DMI and increased steroid catabolism by splanchnic tissues, has been proposed as one of the reasons why lactating cows have shorter and less intense estrus than heifers (Sangsritavong et al., 2002; Sartori et al., 2004). Lopez et al. (2004) demonstrated that high-producing cows (46 kg/d) had reduced estradiol concentration (7.7 ± 0.7 pg/mL vs. 9.6 ± 0.5 pg/mL) and larger

Figure 4. Tornado graphs showing the differences in monetary variables included in the stochastic simulation model: (A) overall, (B) primiparous, and (C) multiparous. Control: Double-Ovsynch protocol started at 55 and 56 (primiparous, herds 1 and 2, respectively) and 41 and 42 (multiparous, herds 1 and 2, respectively) DIM for first postpartum insemination at a fixed time. Re-insemination at estrus detected by herd personnel (herd 1, visual detection; herd 2, visual detection and activation of Estrotect [Rockway Inc., Spring Valley, WI]). TRM: Cows that had at least one estrus (heat index ≥70; 0 = minimum, 100 = maximum) detected by the AMD by 54 and 55 (primiparous; herds 1 and 2, respectively) and 40 and 41 (multiparous; herds 1 and 2, respectively) DIM were inseminated at AMD-detected estrus starting at 64 (primiparous) and 50 (multiparous) DIM. Cows not inseminated within 42 d were submitted to the Double-Ovsynch protocol and fixed-time insemination. Cows not detected in estrus or with a heat index <70 were managed as cows in the control treatment. TRM: Re-insemination upon AMD- and herd personnel-detected estrus, as described for the control treatment. Cows not re-inseminated in estrus were enrolled in the 5-d CO-Synch protocol 5 d before pregnancy diagnosis (d 0, GnRH; d 5 and 6, PGF$_{2\alpha}$; d 8, GnRH and TAI). Blue bars represent outputs. Orange bars represent inputs. AdjGP = adjusted GP; IOFC = income over feed cost; Repro. manag. = reproductive management.

pre-ovulatory follicles (18.0 ± 0.5 mm vs. 16.7 ± 0.4 mm) than low-producing cows (34 kg/d). Using a radio-telemetric transmitter (HeatWatch, DDx, Denver, CO), Lopez et al. (2004) demonstrated that high-producing cows had shorter estrous duration (10.9 ± 0.7 h vs. 6.2 ± 0.5 h), fewer standing events (8.8 ± 0.6 vs. 6.3 ± 0.4 events/estrus), and lesser total standing time (28.2 ± 1.9 vs. 21.7 ± 1.3 s/estrus) than low-producing cows. Using AMD that detect estrus based on changes in patterns of activity and rumination, Marques et al. (2020) and Schilkowsky et al. (2021) demonstrated that the estrus of high-producing cows (44–49 kg/d) was ~1 h shorter than that of low-producing cows (34–38 kg/d) and that the former were less likely to reach activity peak ≥89 (0 = minimum, 100 = maximum; 84.3% ± 1.8% vs. 90.3% ± 1.6%). In the current experiment, cows were housed in barns with concrete flooring in the southeast United States, a location prone to heat stress, environmental conditions associated with diminished signs of estrus (Britt et al., 1986; Tippenhauer et al., 2021). Furthermore, cows produced on average 40.2 kg/d (first lactation), 50.3 kg/d (second lactation), and 53.5 kg/d (≥third lactation) between 60 and 120 DIM. Considering that the probability of detection of estrus in high-producing cows (50 kg/d) was estimated to be ~0.50 and 0.17 when visual observation of standing activity was conducted every 6 and 24 h, respectively (Lopez et al., 2004), it is understandable why AMD-aided estrous detection improved detection of estrus of nonpregnant cows.

As a consequence of the improved reproductive performance, the TRM treatment increased the percentage of cows starting a new lactation and reduced the percentage of cows sold. One of the leading causes of culling in North American dairy herds is the failure to conceive in a timely manner following parturition (de Souza et al., 2023). Therefore, it is not surprising that a reproductive strategy that improved the hazard of pregnancy changed the culling dynamics of the herd. Although revenue from cow sales were reduced in the TRM treatment by approximately $55/cow, replacement cost was lower ($89/cow) and calf value was greater ($10/cow) for the TRM treatment. Surprisingly, the IOFC was not affected by treatments. Often, improvements in reproductive performance are expected to increase the IOFC over the lactation. Cows conceiving earlier postpartum have a shortened calving interval, resulting in a greater proportion of time between 2 calvings at the highest and most efficient milk production phase of their lactation. In the current experiment, milk yield decreased by 0.9% and 1.4% per week among primiparous and multiparous cows, respectively, following the peak of lactation. Consequently, the milk:intake ratio decreased from 1.90 at 50 DIM to 1.40 at 300 DIM among primiparous cows and from 2.0 at 30 DIM to 1.25 at 300 DIM among multiparous cows. Thus, when

improvements in reproductive performance are large, the resulting shortening of the intercalving interval increases the proportion of days between 2 calvings when feed efficiency is highest. Despite improving the hazard of pregnancy, the TRM treatment did not affect DIM, total milk yield, and the estimated DMI during the lactation of cows that started a new lactation, were sold, and died. This may explain why no differences in IOFC were observed between the 2 treatments. Despite a 60% decrease in the use of reproductive hormones among cows in the TRM treatment, the cost of reproductive management was not affected by treatments because the reduced expenditures with reproductive hormones and their administration in the TRM treatment were offset by the cost of AMD and managing it. Therefore, the $108/cow greater GP observed for cows in the TRM treatment was explained by the changes in culling dynamics. Retention pay-off assesses the economic value of keeping a cow in the herd for an additional lactation compared with replacing her with a primiparous cow based on future profitability, factoring in the cow's expected milk production, reproductive status, health risks, and the replacement heifer's costs (De Vries, 2006; Cabrera, 2012). The control treatment increased the number of cows sold, primarily due to reproductive failure, that were replaced with primiparous cows, who have greater RPO by definition. Consequently, the RPO was reduced in the TRM treatment by approximately $25/cow, resulting in a lack of difference between treatments in adjusted GP. Sitko et al. (2023) evaluated the cash flow accumulated over the first and second lactations of primiparous cows receiving the first postpartum AI following a reproductive management that favored AI at AMD-detected estrus versus a management based on OvSP + TAI. Overall, they were not able to identify clear economic advantages for the reproductive management that favored AI at AMD-detected estrus versus the management based on OvSP + TAI, regardless of genetic merit for fertility traits of the cows. The lack of differences in cash flow reflected the minute and inconsistent differences in long-term reproductive performance of the 2 management strategies, limiting differences in culling dynamics and IOFC. Our findings suggest that the benefits of adoption of AMD to the profitability of dairy cows are largely dependent on the reproductive strategy adopted by the herd, the reproductive performance of the herd, and the initial cost and the longevity of the system being purchased, as discussed by others (Rutten et al., 2014; Giordano et al., 2015; Dolecheck et al., 2016a).

According to the stochastic models used in the current experiment, the benefits of implementing the TRM treatment were evident in all the iterations evaluated. The improvements in GP ranged from $67.2/cow to $108.5/cow and in adjusted GP ranged from $54.1/cow to $82.6/cow. Replacement cost, milk price, and cost of estrous detec-tion were positively associated with the differences in GP and adjusted GP between the TRM and control treatments. Thus, as replacement cost, milk price, and cost of estrous detection increased, the difference between the TRM and control treatment increased. Conversely, feed cost of dry cows, cost of AMD, and cow sale value were negatively associated with the differences in GP and adjusted GP between the TRM and control treatments. This demonstrates that as feed cost of dry cows, cost of AMD, and cow sale value increase the differences in GP and adjusted GP between the TRM and control treatment decreased. Among reproductive management variables, the cost of estrous detection and cost of AMD had the highest correlation with differences in GP and adjusted GP between the control and TRM treatments. However, cost of reproductive management explained only ~1% of the variability in GP and adjusted GP. Our findings reinforce the current knowledge that the economic benefits of adopting a new reproductive management depend mainly on the expected improvement in reproductive performance, which affects culling practices and milk production efficiency.

The larger differences in GP between treatments among multiparous cows than primiparous cows may be explained by the fact that the magnitude of the differences between the treatments regarding reproductive outcomes and, consequently, culling policies were more pronounced among multiparous cows. Multiparous cows in the TRM treatment had a 25% greater hazard of pregnancy than those in the control treatment, resulting in a 10% increase in percentage of cows starting a new lactation and a 27% decrease in the percentage of cows sold. Conversely, primiparous cows in the TRM treatment had a 7% greater hazard of pregnancy, resulting in a 3% increase in percentage of cows starting a new lactation and a 23% decrease in the percentage of cows sold. As explained previously, Gonzalez et al. (2023) demonstrated that the pregnancy to first AI was nearly 27% lower among primiparous cows in the TRM treatment compared with those in the control treatment, but the pregnancy to first AI was 8% greater for multiparous cows in the TRM treatment compared with those in the control treatment. Furthermore, primiparous cows from both treatments received ~10% more inseminations and 5% more reproductive examinations than multiparous cows. These differences indicate that primiparous cows were given more opportunities to conceive than multiparous cows, which is corroborated by the fact that the percentage of primiparous and multiparous cows deemed not eligible for AI during their lactation were 4.5% and 10.6%, respectively. We conclude that the increased opportunities for primiparous cows to become pregnant, along with the faster re-insemination in the TRM treatment, mitigated the negative effect of the lower pregnancy risk after the

first AI in the TRM treatment. This prevented primiparous cows in the TRM treatment from having lower GP and adjusted GP than those in the control treatment.

CONCLUSIONS

The TRM treatment improved the GP of Holstein cows in the current experiment by expediting the re-insemination of nonpregnant, which increased the hazard of pregnancy. The consequent altered culling dynamics resulted in reduced replacement costs, increased calf value, and lower revenue from cow sales in the TRM compared with the control treatment. While no differences in adjusted GP were detected after accounting for RPO, stochastic modeling confirmed the economic advantages of the TRM treatment. By addressing the challenges of detecting estrus in high-producing cows, the TRM treatment proved effective in improving reproductive performance and profitability, offering a valuable strategy for dairy producers seeking to optimize reproductive management, reduce reliance on exogenous hormones, and tailor insemination practices according to EPEC.

NOTES

Nonstandard abbreviations used: AdjGP = adjusted GP; AMD = automated monitoring devices; 21-d PR = 21-day pregnancy rate; GP = gross profit; HI = heat index; HO = Holstein; IOFC = income over feed costs; OvSP = ovulation synchronization protocols; P/AI = pregnancies per AI; Ref. = referent; Repro. = reproductive; RPO = retention pay-off; TAI = timed AI; THI = temperature-humidity index; TRM = targeted reproductive management; TRT = treatment.

REFERENCES

Aungier, S. P. M., J. F. Roche, M. Sheehy, and M. A. Crowe. 2012. Effects of management and health on the use of activity monitoring for estrus detection in dairy cows. J. Dairy Sci. 95:2452–2466. https://doi.org/10.3168/jds.2011-4653.

Borchardt, S., C. M. Tippenhauer, J.-L. Plenio, A. Bartel, A. M. L. Madureira, R. L. A. Cerri, and W. Heuwieser. 2021. Association of estrous expression detected by an automated activity monitoring system within 40 days in milk and reproductive performance of lactating Holstein cows. J. Dairy Sci. 104:9195–9204. https://doi.org/10.3168/jds.2020-19705.

Brito, L. F., N. Bedere, F. Douhard, H. R. Oliveira, M. Arnal, F. Peñagaricano, A. P. Schinckel, C. F. Baes, and F. Miglior. 2021. Review: Genetic selection of high-yielding dairy cattle toward sustainable farming systems in a rapidly changing world. Animal 15(Suppl. 1):100292. https://doi.org/10.1016/j.animal.2021.100292.

Britt, J. H., R. G. Scott, J. D. Armstrong, and M. D. Whitacre. 1986. Determinants of estrous behavior in lactating Holstein cows. J. Dairy Sci. 69:2195–2202. https://doi.org/10.3168/jds.S0022-0302(86)80653-1.

Cabrera, V. E. 2012. A simple formulation and solution to the replacement problem: A practical tool to assess the economic cow value, the value of a new pregnancy, and the cost of a pregnancy loss. J. Dairy Sci. 95:4683–4698. https://doi.org/10.3168/jds.2011-5214.

Chebel, R. C., and A. Veronese. 2020. Associations between genomic merit for daughter pregnancy rate of Holstein cows and metabolites postpartum and estrus characteristics. J. Dairy Sci. 103:10754–10768. https://doi.org/10.3168/jds.2020-18207.

de Souza, T. C., L. F. B. Pinto, V. A. R. da Cruz, H. R. de Oliveira, V. B. Pedrosa, G. A. Oliveira Jr., F. Miglior, F. S. Schenkel, and L. F. Brito. 2023. A comprehensive characterization of longevity and culling reasons in Canadian Holstein cattle based on various systematic factors. Transl. Anim. Sci. 7:txad102. https://doi.org/10.1093/tas/txad102.

Denis-Robichaud, J., R. L. A. Cerri, A. Jones-Bitton, and S. J. LeBlanc. 2018. Performance of automated activity monitoring systems used in combination with timed artificial insemination compared to timed artificial insemination only in early lactation in dairy cows. J. Dairy Sci. 101:624–636. https://doi.org/10.3168/jds.2016-12256.

De Vries, A. 2006. Economic value of pregnancy in dairy cattle. J. Dairy Sci. 89:3876–3885. https://doi.org/10.3168/jds.S0022-0302(06)72430-4.

Dolecheck, K. A., G. Heersche Jr., and J. M. Bewley. 2016a. Retention payoff–based cost per day open regression equations: Application in a user-friendly decision support tool for investment analysis of automated estrus detection technologies. J. Dairy Sci. 99:10182–10193. https://doi.org/10.3168/jds.2015-10364.

Dolecheck, K. A., W. J. Silvia, G. Heersche Jr., C. L. Wood, K. J. McQuerry, and J. M. Bewley. 2016b. A comparison of timed artificial insemination and automated activity monitoring with hormone intervention in 3 commercial dairy herds. J. Dairy Sci. 99:1506–1514. https://doi.org/10.3168/jds.2015-9914.

Economic Research Service. 2024. Milk Cost of Production Estimates. USDA, Washington, DC. Accessed Jan. 10, 2024. https://www.ers.usda.gov/data-products/milk-cost-of-production-estimates/milk-cost-of-production-estimates/#Recent%20Milk%20Cost%20of%20Production%20Estimates-2016%20Base.

Evink, T. L., and M. I. Endres. 2017. Management, operational, animal health, and economic characteristics of large dairy herds in 4 states in the Upper Midwest of the United States. J. Dairy Sci. 100:9466–9475. https://doi.org/10.3168/jds.2016-12179.

Ferguson, J. D., D. T. Galligan, and N. Thomsen. 1994. Principal descriptors of body condition score in Holstein cows. J. Dairy Sci. 77:2695–2703. https://doi.org/10.3168/jds.S0022-0302(94)77212-X.

Fricke, P. M., P. D. Carvalho, J. O. Giordano, A. Valenza, G. Lopes Jr., and M. C. Amundson. 2014. Expression and detection of estrus in dairy cows: The role of new technologies. Animal 8(Suppl. 1):134–143. https://doi.org/10.1017/S1751731114000299.

Fricke, P. M., and M. C. Wiltbank. 2022. *Symposium review:* The implications of spontaneous versus synchronized ovulations on the reproductive performance of lactating dairy cows. J. Dairy Sci. 105:4679–4689. https://doi.org/10.3168/jds.2021-21431.

Galvão, K. N., P. Federico, A. De Vries, and G. M. Schuenemann. 2013. Economic comparison of reproductive programs for dairy herds using estrus detection, timed artificial insemination, or a combination. J. Dairy Sci. 96:2681–2693. https://doi.org/10.3168/jds.2012-5982.

Giordano, J. O., P. M. Fricke, M. C. Wiltbank, and V. E. Cabrera. 2011. An economic decision-making support system for selection of

reproductive management programs on dairy farms. J. Dairy Sci. 94:6216–6232. https://doi.org/10.3168/jds.2011-4376.

Giordano, J. O., A. S. Kalantari, P. M. Fricke, M. C. Wiltbank, and V. E. Cabrera. 2012. A daily herd Markov-chain model to study the reproductive and economic impact of reproductive programs combining timed artificial insemination and estrus detection. J. Dairy Sci. 95:5442–5460. https://doi.org/10.3168/jds.2011-4972.

Giordano, J. O., M. L. Stangaferro, R. Wijma, W. C. Chandler, and R. D. Watters. 2015. Reproductive performance of dairy cows managed with a program aimed at increasing insemination of cows in estrus based on increased physical activity and fertility of timed artificial inseminations. J. Dairy Sci. 98:2488–2501. https://doi.org/10.3168/jds.2014-8961.

Gonzalez, T. D., L. Factor, A. Mirzaei, A. B. Montevecchio, S. Casaro, V. R. Merenda, J. G. Prim, K. N. Galvão, R. S. Bisinotto, and R. C. Chebel. 2023. Targeted reproductive management for lactating Holstein cows: Reducing the reliance on exogenous reproductive hormones. J. Dairy Sci. 106:5788–5804. https://doi.org/10.3168/jds.2022-22666.

Lopez, H., L. D. Satter, and M. C. Wiltbank. 2004. Relationship between level of milk production and estrous behavior of lactating dairy cows. Anim. Reprod. Sci. 81:209–223. https://doi.org/10.1016/j.anireprosci.2003.10.009.

Marques, O., A. Veronese, V. R. Merenda, R. S. Bisinotto, and R. C. Chebel. 2020. Effect of estrous detection strategy on pregnancy outcomes of lactating Holstein cows receiving artificial insemination and embryo transfer. J. Dairy Sci. 103:6635–6646. https://doi.org/10.3168/jds.2019-17892.

Merenda, V. R., D. Lezier, A. Odetti, C. C. Figueiredo, C. A. Risco, R. S. Bisinotto, and R. C. Chebel. 2021. Effects of metritis treatment strategies on health, behavior, reproductive, and productive responses of Holstein cows. J. Dairy Sci. 104:2056–2073. https://doi.org/10.3168/jds.2020-19076.

National Agricultural Statistics Service. 2022. Quick Stats. USDA, Washington, DC. Accessed Jan. 10, 2024. https://quickstats.nass.usda.gov/results/C036B1BE-653C-392A-865A-714795334E81.

National Agricultural Statistics Service. 2024a. Quick Stats. USDA, Washington, DC. Accessed Jan. 10, 2024. https://quickstats.nass.usda.gov/results/70826CF5-A4E4-3264-823D-FD0E20C531F7.

National Agricultural Statistics Service. 2024b. Rising farm worker wages suggest tightening farm labor markets. USDA, Washington, DC. Accessed Jan. 10, 2024. https://www.nass.usda.gov/Statistics_by_State/Regional_Office/Southern/includes/Publications/Economic_and_Demographic_Releases/Farm_Labor/2022/AprilLabor2022.pdf.

NRC. 2001. Nutrient Requirements of Dairy Cattle. 7th rev. ed. National Academies Press, Washington, DC.

NRC. 2021. Nutrient Requirements of Dairy Cattle. 8th rev. ed. National Academies Press, Washington, DC.

Olynk, N. J., and C. A. Wolf. 2007. Expected net present value of pure and mixed sexed semen artificial insemination strategies in dairy heifers. J. Dairy Sci. 90:2569–2576. https://doi.org/10.3168/jds.2006-460.

Pieper, L., M. G. Doherr, and W. Heuwieser. 2016. Consumers' attitudes about milk quality and fertilization methods in dairy cows in Germany. J. Dairy Sci. 99:3162–3170. https://doi.org/10.3168/jds.2015-10169.

Rial, C., A. Laplacette, and J. O. Giordano. 2022. Effect of a targeted reproductive management program designed to prioritize insemination at detected estrus and optimize time to insemination on the reproductive performance of lactating dairy cows. J. Dairy Sci. 105:8411–8425. https://doi.org/10.3168/jds.2022-22082.

Rutten, C. J., W. Steeneveld, C. Inchaisri, and H. Hogeveen. 2014. An ex ante analysis on the use of activity meters for automated estrus detection: To invest or not to invest? J. Dairy Sci. 97:6869–6887. https://doi.org/10.3168/jds.2014-7948.

Sangsritavong, S., D. K. Combs, R. Sartori, L. E. Armentano, and M. C. Wiltbank. 2002. High feed intake increases liver blood flow and metabolism of progesterone and estradiol-17 beta in dairy cattle. J. Dairy Sci. 85:2831–2842. https://doi.org/10.3168/jds.S0022-0302(02)74370-1.

Santos, J. E. P., C. D. Narciso, F. Rivera, W. W. Thatcher, and R. C. Chebel. 2010. Effect of reducing the period of follicle dominance in a timed artificial insemination protocol on reproduction of dairy cows. J. Dairy Sci. 93:2976–2988. https://doi.org/10.3168/jds.2009-2870.

Sartori, R., J. M. Haughian, R. D. Shaver, G. J. Rosa, and M. C. Wiltbank. 2004. Comparison of ovarian function and circulating steroids in estrous cycles of Holstein heifers and lactating cows. J. Dairy Sci. 87:905–920. https://doi.org/10.3168/jds.S0022-0302(04)73235-X.

Schilkowsky, E. M., G. E. Granados, E. M. Sitko, M. Masello, M. M. Perez, and J. O. Giordano. 2021. Evaluation and characterization of estrus alerts and behavioral parameters generated by an ear-attached accelerometer-based system for automated detection of estrus. J. Dairy Sci. 104:6222–6237. https://doi.org/10.3168/jds.2020-19667.

Schulz, L. 2020. Historical cattle prices. Ag Decision Maker. Extension and Outreach, Iowa State University. Accessed Nov. 19, 2024. https://www.extension.iastate.edu/agdm/livestock/pdf/b2-12.pdf.

Sitko, E., F. Di Croce, A. McNeel, D. Weigel, and J. Giordano. 2023. Effect of reproductive management programs that prioritized artificial insemination at detected estrus or timed artificial insemination on the economic performance of primiparous Holstein cows of different genetic merit for fertility. J. Dairy Sci. 106:6495–6514. https://doi.org/10.3168/jds.2022-22674.

Souza, A. H., H. Ayres, R. M. Ferreira, and M. C. Wiltbank. 2008. A new presynchronization system (Double-Ovsynch) increases fertility at first postpartum timed AI in lactating dairy cows. Theriogenology 70:208–215. https://doi.org/10.1016/j.theriogenology.2008.03.014.

Stangaferro, M. L., R. Wijma, M. Masello, M. J. Thomas, and J. O. Giordano. 2018. Extending the duration of the voluntary waiting period from 60 to 88 days in cows that received timed artificial insemination after the Double-Ovsynch protocol affected the reproductive performance, herd exit dynamics, and lactation performance of dairy cows. J. Dairy Sci. 101:717–735. https://doi.org/10.3168/jds.2017-13046.

Tippenhauer, C. M., J. L. Plenio, A. M. L. Madureira, R. L. A. Cerri, W. Heuwieser, and S. Borchardt. 2021. Factors associated with estrous expression and subsequent fertility in lactating dairy cows using automated activity monitoring. J. Dairy Sci. 104:6267–6282. https://doi.org/10.3168/jds.2020-19578.

USDA. 2014. Dairy 2014: Health and management practices on U.S. dairy operations, 2014. Accessed Jan. 10, 2024. https://www.aphis.usda.gov/animal_health/nahms/dairy/downloads/dairy14/Dairy14_dr_PartIII.pdf.

van Arendonk, J. A. M. 1985. A model to estimate the performance, revenues and costs of dairy cows under different production and price situations. Agric. Syst. 16:157–189. https://doi.org/10.1016/0308-521X(85)90010-1.

Walker, S. L., R. F. Smith, J. E. Routly, D. N. Jones, M. J. Morris, and H. Dobson. 2008. Lameness, activity time-budgets, and estrus expression in dairy cattle. J. Dairy Sci. 91:4552–4559. https://doi.org/10.3168/jds.2008-1048.

Wiltbank, M. C., and J. R. Pursley. 2014. The cow as an induced ovulator: timed AI after synchronization of ovulation. Theriogenology 81:170–185. https://doi.org/10.1016/j.theriogenology.2013.09.017.