Tropical Animal Health and Production (2023) 55:149
https://doi.org/10.1007/s11250-023-03559-7

REGULAR ARTICLES

Early versus late body condition score loss in dairy cows: Reproductive performance

Luiz Francisco Machado Pfeifer[1,2] · Rhuan Amorim de Lima[1,3] · Sidnei Hiroki Nakashima[4] · Jackeline Thaís da Silva[4] · Eduardo Schmitt[5]

Received: 13 September 2022 / Accepted: 29 March 2023

Abstract

This study aimed to compare milk production and reproductive performance in high yield Holstein cows that lose BCS early and late in the postpartum period. Lactating dairy cows (n = 76) were received first timed AI at 60 to 75 DIM using the farm-managed estradiol-progesterone-GnRH–based timed AI protocol. The BCS of all cows was daily evaluated by automated BCS cameras. Aiming to evaluate the effect of the days in milk (DIM) in which a cow reached the nadir BCS on the reproductive parameters, cows were separated into two groups: early BCS loss ($n = 42$), cows that reached the nadir BCS ≤ 34 DIM, and late BCS loss ($n = 34$), cows that reached the nadir BCS > 34 DIM. The optimal cut-off point for determining the relationship between days to nadir BCS and pregnancy by 150 DIM (P150) was calculated using the receiver operating characteristic (ROC) curve. From the ROC analysis, the cut-off was 34 DIM (Se, 80.9%; Sp, 66.7%; AUC, 0.74; $P < 0.01$). No differences (P>0.05) were detected between groups on the BCS and milk production. The average of milk production in both groups was 46.65 ± 6.15 Kg/day. Cows that reached the nadir BCS early postpartum presented lower ($P < 0.01$) calving interval and greater ($P < 0.01$) pregnancy at first AI and P150. In summary, cows that lost BCS early had better reproductive performance and had similar milk yield compared with cows that lost BCS late in the postpartum period.

Keywords Milk · Ovulation · Pregnancy · Timed AI

Introduction

Dairy cows commonly lose body condition score (BCS) in the postpartum period due to physiological changes at the beginning of lactation that impact their metabolism. Several studies on dairy cows have quantified the effect of BCS on health (Markusfeld et al., 1997; Berry et al. 2007; Middleton et al., 2019), fertility (Gillund et al. 2001; Roche et al. 2007a; Carvalho et al., 2014; Gobikrushanth et al., 2019; Middleton et al., 2019), and milk yield (Waltner et al. 1993; Ruegg and Milton 1995; Domecq et al. 1997; Gobikrushanth et al., 2019). Cows that lose less or maintain BCS during the first weeks of lactation have lower serum concentrations of β-hydroxy-butyrate (ßHB) and non-esterified fatty acids (NEFA; Carvalho et al., 2014; Barletta et al., 2017), a decrease in the incidence of clinical and subclinical metabolic diseases and a reduction in calving interval, which enables these females to reach high fertility cycles (HFC) and, consequently, to exhibit calving intervals of up to 13 months (Middleton *et al.* 2019). These HFC, which should be the goal for milk production systems, are productive cycles where cows have reduced loss of BCS during the postpartum period (PPP) and, consequently, are more likely to conceive at the beginning of the service period.

The intrinsic ability of a dairy cow to address the energy requirements demanded by lactation will determine its health and, consequently, its reproductive performance during the PPP (Ribeiro et al. 2013). In this regard, BCS is an important marker of cow health and an useful tool

✉ Luiz Francisco Machado Pfeifer
luiz.pfeifer@embrapa.br

1 Empresa Brasileira de Pesquisa Agropecuária (EMBRAPA), Porto Velho, RO, Brazil

2 Embrapa Rondonia, BR 364 - Km 5,5 - Zona Rural, Caixa postal: 127 CEP, Porto Velho, Rondonia 76815-800, Brazil

3 Programa de Pós-Graduação em Biodiversidade e Biotecnologia da Rede Bionorte (BIONORTE), Porto Velho, RO, Brazil

4 DeLaval Brasil Ltda, Jaguariúna, SP, Brazil

5 NUPEEC, Universidade federal de Pelotas (UFPel), Pelotas, Brazil

for monitoring the nutritional status of dairy herds (Heuer et al. 1999). Several studies demonstrated that cows with low BCS or loss of body condition have fewer pregnancies per AI (P/AI) at first service (Domecq et al., 1997; Moreira et al., 2000; Santos et al., 2009, Gobikrushanth et al., 2019). Furthermore, Carvalho et al. (2014) reported a significant increase in P/AI if cows gained or maintained BCS during the first 3-week postpartum.

Numerous of early studies observed a strong negative relationship between BCS at calving and change in BCS during early lactation (Garnsworthy, 1988; Treacher et al., 1986; Garnsworthy and Jones, 1987; Bourchier et al., 1987). According to Garnsworthy (2007), each dairy cow has a genetically programmed target BCS that she attempts to reach approximately 10 to 12 weeks after calving. Other studies have focused to establish the relationship between the dynamic of BCS postpartum (loss, maintenance, or gain), milk production, and reproductive performance (Gobikrushanth et al., 2019). Other studies also observed a strong relationship between postpartum loss of BCS and fertility (López-Gatius et al., 2003; Chapinal et al., 2012).

Although the BCS has been used as a tool for managing dairy herds since the 1970s (Lowman et al. 1976) and there is extensive literature that endorses its importance (Edmonson et al. 1989; Waltner et al. 1993; Domecq, et al. 1997; Moreira et al. 2000; Pryce et al. 2000), the relationship between the days in milk (DIM) to nadir BCS and the reproductive performance in high yield dairy cows has not been investigated. Cows that experience extreme loss of BCS need longer postpartum periods to return ovarian activity and had lower reproductive performance than cows that had a moderate loss of BCS or cows that maintained or gained BCS in the postpartum period (Gobikrushanth et al., 2019). In contrast, one can speculate that cows that quickly lose BCS postpartum and soon start recovering BCS may experience better reproductive performance than cows that takes longer to reach the nadir BCS.

Based on these considerations, the objective of this study was to compare reproductive performance and milk production in high-yield Holstein cows that lose BCS early and late in the postpartum period. This study hypothesizes that cows that lose BCS early have better reproductive performance than cows that lose BCS later in the postpartum period.

Material and methods

Animals, housing, and AI

This experiment was conducted on a commercial dairy farm in Carambeí, PR, Brazil. Lactating dairy cows (*n* = 76) were housed in freestall facilities bedded with sand and had ad libitum access to fresh feed and water. Cows were milked 3 times daily. Cows were fed TMR diets using corn and alfalfa silage as forage and corn- and soybean meal-based concentrates and supplemented with minerals and vitamins. The TMR diets were balanced by a professional nutritionist using the NRC (2001) nutritional requirements for lactating dairy cows. All cows in the commercial farms received bST every 11 days beginning at 60 DIM (500 mg/dose; Posilac; Monsanto Co., St Louis, MO), until dry-off. Cows received first timed AI at 60 to 75 DIM using the farm-managed at estradiol-progesterone-GnRH–based timed AI protocol. Cows received an intravaginal P4-releasing insert (Repro Sync®, GlobalGen Vet Science, Brasil), 10.5 µg i.m. of GnRH de (2.5 mL of Gonaxal®, Biogénesis Bagó, Argentina), 2 mg i.m. of estradiol benzoate (2.5 mL of Syncrogen®, GlobalGen Vet Science, Brasil) on day 0; 0.5 mg i.m. of cloprostenol (2 mL of Induscio®, GlobalGen Vet Science, Brasil) on day 7; 0.5 mg i.m. of cloprostenol (2 mL de Induscio®, GlobalGen Vet Science, Brasil), 1 mg i.m. of estradiol cypionate (0.5 mL of Cipion®, GlobalGen Vet Science, Brasil), and the withdrawal of the P4 insert on day 8. All cows received 10.5 µg i.m. of GnRH (2.5 mL of Gonaxal®, Biogénesis Bagó, Argentina) and were inseminated on day 10.

Pregnancy diagnosis was performed 30 days after TAI using a portable scanner (Ibex Pro; E. I. Medical Imaging, Loveland, CO) fitted with a 7.5-MHz linear-array transducer.

Reproductive data such as calving date, date of AI, pregnancy diagnosis, BCS, and milk production were collected from the DelPro Farm Manager.

BCS evaluation

The BCS of all cows was daily evaluated by BCS cameras (DeLaval body condition scoring BCS, DeLaval International AB, Tumba, Sweden), which were mounted on the sort gate at the exit where cows passed through daily post-milking. As the cow passed under the mounted camera, a continuous video (30 FPS, 32,000 captured reference points) was taken, and a 3D image from the video was automatically created and saved by the BCS camera software. In a secondary step, the saved 3D images were processed through an algorithm and analyzed to locate the key physical characteristics (pins, tail head ligaments, thurl, sacral ligaments, short ribs, and hooks) of the cow to calculate the automated score, viewable in DelPro Farm Manager (DeLaval International AB, Tumba, Sweden). The algorithm is based on the BCS scoring proposed by earlier studies but was reported in 0.1 increments in this study (Ferguson et al., 1994; Spoliansky et al., 2016). All automated BCS data were recorded and downloaded from DelPro Farm Manager.

Experimental groups

Aiming to evaluate the effect of the DIM of the BCS nadir on the reproductive parameters, cows were separated into two groups: early BCS loss (n = 42), cows that reached the nadir of BCS ≤ to 34 DIM, and late BCS loss (n = 34), cows that reached the nadir of BCS > 34 DIM.

The optimal cut-off point for DIM of the nadir of BCS effects in pregnancy by 150 DIM (P150) was calculated using the receiver operating characteristic (ROC) curve and was determined based on the highest sensitivity (Se) and specificity (Sp). Area under the curve (AUC), Se, Sp, and P value of the ROC test are reported. Therefore, 34 DIM was the cut-off value that better establish a relationship between the DIM in which cows reached the nadir of BCS and the P150. The P150 was chosen as a reference due to cows that became pregnant by 150 DIM presented economic advantages and adequate reproductive performance (calving intervals of ~14 months; adapted from Arbel et al., 2001).

Definitions and statistical analysis

Statistical analyses were performed using the SAS program (SAS Institute Inc., Cary, NC, USA), except for ROC calculations and Kaplan-Meier survival analysis, which were performed using GraphPad Prism 5 software (GraphPad Software Inc., La Jolla, CA, USA). For statistical purposes, cows were also categorized for BCS at calving in low (< 3, n = 10), adequate (≥ 3 BCS ≤ 3.5, n = 45), and high BCS (> 3.5, n = 21) and according to the lactation number in younger (< 3 lactations, n = 46) and older cows (≥ 3 lactations, n = 30).

Optimal cut-off points for determining the relationship between the DIM of the nadir of BCS and P150 were calculated using the receiver operating characteristic (ROC) curve. Therefore, cows were separated according to the DIM of the nadir of BCS in early and late DIM. The initial analysis for binomial analyses included the effect of group, BCS at calving, lactation number, and sire. Lactation number, BCS at calving, and sire had no significant effect and were, therefore, excluded from the final statistical model. Then, pregnancy per AI was compared between these groups by chi-square test.

For the continuous variables such as BCS at calving, the nadir of BCS, DIM of the nadir of BCS, BCS loss, and calving interval, the initial analysis included the effect of BCS at calving, lactation number, and group in the statistical model. When one of the main effect presented significance, it was held in the model, and then factorial ANOVA was used to detect the effect of BCS at calving, lactation number, and their interactions with the group (early vs. late). The group effect was held in all analyses independently of significance.

All data obtained from the repeat measurements (BCS and milk production) were compared between groups by ANOVA using the mixed procedure to evaluate the main effects of group, time, and their interactions.

Kaplan-Meier survival analysis curves were constructed to illustrate the rate at which cows became pregnant using the Kaplan-Meier survival analysis features of GraphPad Prism 5 software.

Results

The P values of the main effects for each parameter evaluated in this study are shown in Table 1. An effect of BCS at calving on the nadir of BCS was detected (Table 1; P = 0.02). However, no BCS at calving*group interaction was detected (P = 0.33). The lowest BCS detected for cows considered with low, adequate, and high BCS were 2.5 ± 0.13, 2.72 ± 0.06, and 2.94 ± 0.09 of BCS, respectively.

There was an effect (P = 0.04) of lactation number on the DIM of the nadir of BCS. Cows with ≥ 3 lactations achieved the nadir of BCS at 36.5 ± 6.3 DIM, whereas cows with ≤ 2 lactations achieved the nadir of BCS at 53.2 ± 5.1 DIM. However, no lactation number*group interaction was detected (P = 0.26).

Table 1. Probability values of the parameters evaluated in the study according to the main effects

Parameter	Effects			
	Group	Number of lactations	BCS at calving	Sire
BCS at calving	0.35	0.22	-	-
Nadir of BCS	0.62	0.46	0.02	-
DIM of the nadir of BCS, days	<0.0001	0.04	0.42	-
BCS loss*	0.58	0.78	0.21	-
Calving interval, days	<0.001	0.48	0.69	-
Pregnancy by first AI, %	0.01	0.9	0.86	0.8
Pregnancy by 150 DIM, %	0.001	0.3	0.29	0.7

*Units of BCS lost from calving to the nadir of BCS

From the ROC analysis for determining the relationship between the DIM to nadir BCS and P150, the cut-off was ≤ 34 DIM (Se, 80.9%; Sp, 66.7%; AUC, 0.74; P < 0.01; Fig. 1). No differences (P>0.05) were detected between groups on the BCS (Fig. 2A) and milk production (Fig. 2B) throughout the lactation period. However, there were an effect of time (P<0.05) and the interaction time*Group (P< 0.05) for BCS and milk production (Fig. 2). The average milk production in both groups was 46.65 ± 6.15 Kg/day. The average calving-to-pregnancy interval differed (P = 0.01) between groups (Fig. 3). Cows in the early group get pregnant early than cows from the Late group.

No effects (P>0.05) of BCS at calving, the nadir of BCS, and postpartum BCS loss were observed between groups (Table 2). However, cows that reached the nadir of BCS early postpartum presented shorter (P<0.0001) DIM of the nadir of BCS, shorter (P < 0.001) calving interval, and greater (P<0.01) pregnancy at first AI and pregnancy at 150 DIM (Table 2).

Discussion

The hypothesis of this study was confirmed; cows that lost BCS early postpartum have lower calving interval and greater pregnancy at first AI and P150. However, no differences were observed in milk production and BCS between cows that lost early and late BCS postpartum.

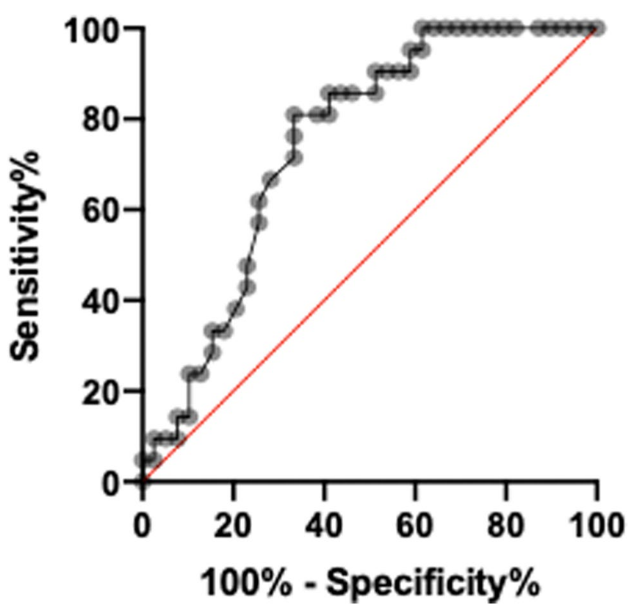

Fig. 1 Receiver operating characteristic (ROC) curve for determining the relationship between the DIM in which cows reached the nadir of BCS and the pregnancy by 150 DIM. The cut-off for DIM in which cows reached the nadir of BCS was 34 (80.9% sensitivity and 66.7% specificity; AUC 0.74; P < 0.01)

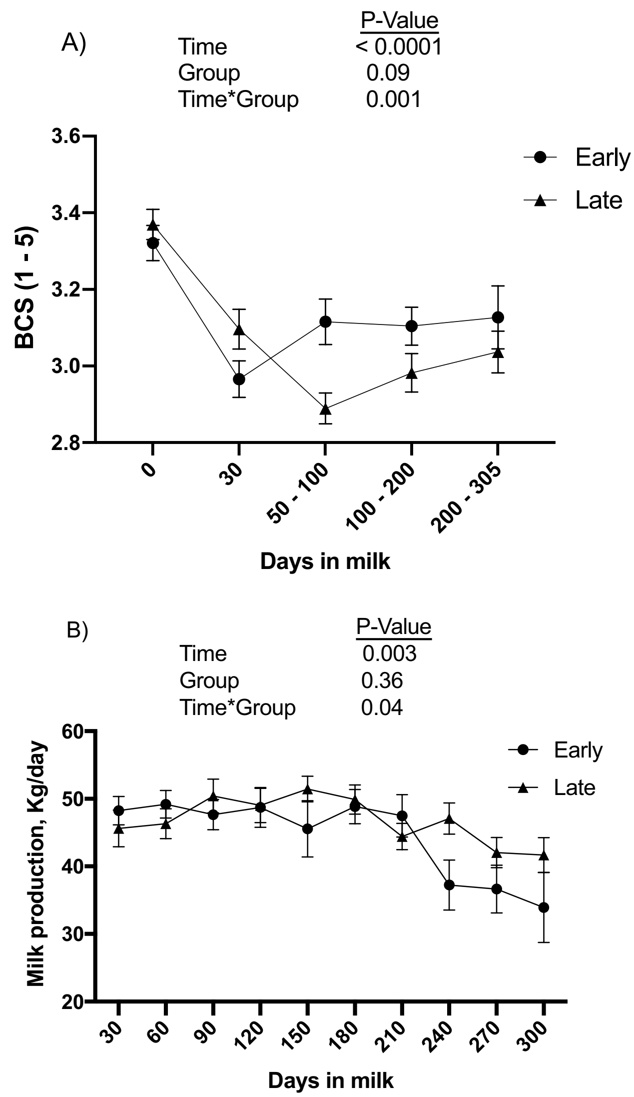

Fig. 2 Body condition score (**A**) and daily milk production (**B**) in Holstein cows that reached the nadir of BCS early and late postpartum

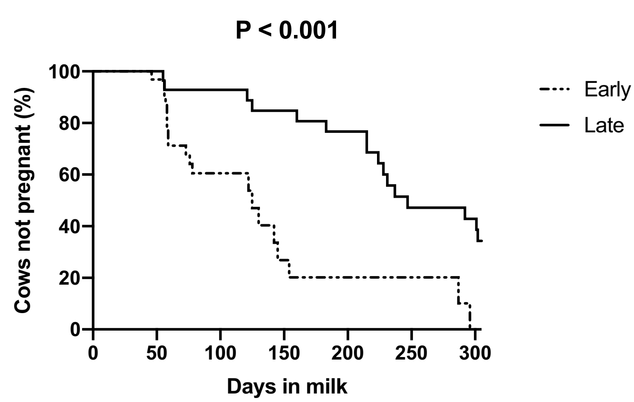

Fig. 3 Kaplan-Meier survival analysis of calving-to-pregnancy interval for cows that reached the nadir of BCS early and late postpartum

Table 2. Dynamics of the BCS and reproductive parameters in Holstein cows that reached the nadir of BCS early and late postpartum

Parameter	Group		*P* value
	Early	Late	
BCS at calving	3.31 ± 0.04	3.37 ± 0.05	0.35
Nadir of BCS	2.78 ± 0.06	2.73 ± 0.07	0.62
DIM of the nadir of BCS, days	23.1 ± 3.8	75.6 ± 4.1	<0.0001
BCS loss*	0.58 ± 0.07	0.64 ± 0.07	0.58
Calving interval, days	376.5 ± 19	479.5 ± 20	<0.001
Pregnancy by first AI, %	30.9 (13/42)	8.8 (3/34)	0.01
Pregnancy by 150 DIM, %	52.4 (22/42)	14.7 (5/34)	0.001

*Units of BCS lost from calving to the nadir of BCS

Although the hypothesis of this study was confirmed, more studies are necessary to clarify the relationship between the DIM to nadir BCS, the DMI, and the reproductive performance. The relationship between BCS loss and reproductive efficiency is well known (Lopez-Gautius et al., 2003, Carvalho 2014, Gobikrushanth et al., 2019, Manríquez et al., 2021). Cows that experience extreme loss of BCS need longer postpartum periods to return ovarian activity and had lower pregnancy to first AI and P150 than cows that had moderate BCS or cows that maintained or gained BCS in the postpartum period (Gobikrushanth et al., 2019). Similarly, Middleton et al. (2019) observed that cows that lost less BCS postpartum had less calving interval. However, to the best of our knowledge, no study was designed to investigate the close relationship between days to nadir BCS and DIM.

In an early study Garnsworthy and Topps (1982) observed that although milk peaked in week 6 of lactation in cows that calved thin, medium, and fat, the maximum dry matter intake (DMI) was reached in week 15 for fat, week 11 for medium cows, and week 9 for thin cows. This suggests that cows have a target BCS that they try to attain during lactation. Moreover, according to these authors, the level of body fat had a direct effect on feed intake. Similarly, in the present study, cows that anticipate the days to nadir BCS may also anticipate the increase in the DMI and, consequently, the BCS recovery and the ingress in a positive energy balance which improve the metabolic condition and the reproductive efficiency in comparison with cows that reached days to nadir BCS later in the lactation. Adequate management of energy body reserves in the transitional period of dairy cows reflects their productive potential, especially for high yielding cows. Therefore, the identification of these cows that are more likely to solve their metabolic condition early postpartum may reflect in better income for dairy producers.

In the present study, we observed that cows that lose BCS early postpartum are gaining BCS by the end of the voluntary wait period and by the first postpartum AI service. In contrast, cows that reached the nadir BCS late in postpartum start increasing BCS after 75 DIM. Even moderate levels of fat tissue mobilization are known to be associated with BEN and reduced fertility in postpartum cows. Several studies indicate that excessive loss of BCS units during the PPP is associated with increased serum concentrations of NEFA, and reduced insulin, as well as with delayed first postpartum ovulation, and reduced pregnancy in the first postpartum AI (Butler et al. 2003; Carvalho, et al. 2014; Middleton et al. 2019). Butler (2005) concluded that there is a 10% reduction in conception rate at first postpartum AI for each BCS unit lost during the PPP. These studies indicate that the loss of BCS units is directly related to reduced fertility during the PPP. In that regard, reducing BCS losses during the PPP increases the chances of cows to reach HFC.

The measurement of residual feed intake in high yielding dairy cows has suggested the possibility of selecting more efficient cows based on the energy balance, milk yield, and health parameters in early lactation. Some cows have lower feed intake and energy balance with no differences in body energy or N changes or yield of energy-corrected milk in early lactation (Marinho et al. 2021). Although the present study did not evaluate feed efficiency, the better reproductive performance observed in cows that reach nadir BCS early could suggest that these cows are more efficient than cows that reach nadir BCS late. Recently, a study observed that the odds of pregnancy at 150 DIM in cows that gain BCS were 1.61 times greater than in cows that had an excessive loss from DIM 5 to DIM 40 (Manríquez et al., 2021). Taken together, these data with the data from the present study demonstrate that not only the amount of BCS loss, but the time in which these losses occur is also important. After calving, BCS changes are associated with the resumption of DMI capacity, which might be related to changes in plasma NEFA concentration (Allen, 2014) and the signal from the hepatic oxidation of fuels (Allen et al., 2009). In this regard, the quality and forage canopy height could help change the source of volatile fatty acids produced in the rumen, manipulating the length of negative energy balance (Moore and DeVries, 2020, Piantoni and VandeHaar, 2023). Especially in tropical regions, in which the dairy system of production is forage-based, new alternatives with high-protein tropical forages can be used as protein banks, creating new alternatives to accelerate the resumption of the DMI capacity after calving.

Although the cows enrolled in the present study had different postpartum BCS dynamics, the milk yield was not different between groups. Studies performed to evaluate the effect of BCS on milk production in dairy cows have shown inconsistent results. Some have reported no effect of BCS at calving on subsequent lactation (Pedron et al. 1993; Ruegg and Milton 1995; Domecq, et al. 1997). However, the more consistent finding reported across studies is an association between a greater loss of BCS and higher milk production (Ruegg and Milton 1995; Domecq, et al. 1997; Roche, et al.

2007b). Grainger et al. (1982) reported an increase in milk production at the beginning of lactation associated with an increase in the BCS at calving. Similarly, Berry et al. (2007) observed that Holstein cows in a grazing system with high BCS at calving (4.25 units, 1–5 scale) had higher total milk production during 305 DIM and less lactation persistence.

BCS is an important marker to estimate body reserves, as well as the nutritional condition of dairy herds, with direct impacts on the productive efficiency of the system. The present study demonstrated that cows that lost BCS early postpartum have better reproductive performance with no effect on milk production. Although the results of this study observed the effect of days to nadir BCS on the calving interval and P/AI at first AI, further research is warranted to understand the biological processes associated with the time of loss of BCS and its association with reproductive performance in dairy cows. Finally, by identifying cows that are still losing BCS after 34 DIM, adjustments can be made to their diets or management strategies to increase their BCS. The results of the present study may stimulate dairy farmers and technicians to monitor BCS at a certain frequency, at least every 15 days after calving. This can lead to improved reproductive efficiency, overall health, and welfare of the cow.

Author contributions LFMP and RAL were responsible for designing the research, conducting the trial, writing the manuscript, and analyzing the data. SN and JTS were responsible for data collection. ES conducted statistical analyses and revised the manuscript. All authors read and approved the manuscript.

Funding This project received funding support from Embrapa (MP1/PC3 Project n. 01.03.14.011.00.00) and from CNPq (Universal Project n: 407307/2016-8).

Data availability Data will be made available on reasonable request.

Code availability Not applicable.

Declarations

Ethics approval The Committee for Ethics in Animal Experimentation of the Brazilian Agricultural Research Corporation (Embrapa - Rondônia) approved all animal handling and procedures.

Consent to participate The author agreed to participate in the article.

Consent for publication The author allows the publication of the manuscript.

Conflict of interest The authors declare no competing interests.

References

Allen, M.S., Bradford, B.J., Oba, M., 2009. Board-invited review: The hepatic oxidation theory of the control of feed intake and its application to ruminants. Journal of Animal Science, 87, 3317–3334.

Allen, M. S., 2014. Drives and limits to feed intake in ruminants. Animal Production Science, 54, 1513–1524.

Arbel, R., Bigun, Y., Ezra, E., Sturman, H., and Hojman, D., 2001. The effect of extended calving intervals in high-yielding lactating cows on milk production and profitability. Journal of Dairy Science 84, 600–608.

Barletta, R. V., Maturana Filho, M., Carvalho, P. D., Del Valle, T. A., Netto, A. S., Rennó, F. P., Mingoti, R. D., Gandra, J. R., Mourão, G. B., Fricke, P. M., Sartori, R., Madureira, E. H., and Wiltbank, M. C., 2017. Association of changes among body condition score during the transition period with NEFA and BHBA concentrations, milk production, fertility, and health of Holstein cows. Theriogenology, 104, 30–36.

Berry, D. P., Buckley, F., and Dillon, P., 2007. Body condition score and live-weight effects on milk production in Irish Holstein-Friesian dairy cows. Animal, 1(9), 1351–1359.

Bourchier, C.P., Garnsworthy, P.C., Hutchinshon, J.M., and Benton, T.A., 1987. The relationship between milk yield and fertility estimated using random regression models. Journal of Dairy Science, 86, 3704-3717.

Butler, S., Marr, A., Pelton, S., Radcliff, R., Lucy, M., and Butler, W., 2003. Insulin restores GH responsiveness during lactation-induced negative energy balance in dairy cattle: effects on expression of IGF-I and GH receptor 1A. Journal of Endocrinology, 176, 205-217.

Carvalho, P. D., Souza, A. H., Amundson, M. C., Hackbart, K. S., Fuenzalida, M. J., Herlihy, M. M., Ayres, H., Dresch, A. R., Vieira, L. M., Guenther, J. N., Grummer, R. R., Fricke, P. M., Shaver, R. D., and Wiltbank, M. C., 2014. Relationships between fertility and postpartum changes in body condition and body weight in lactating dairy cows. Journal of Dairy Science, 97(6), 3666–3683.

Chapinal, N., S. J. LeBlanc, M. E. Carson, K. E. Leslie, S. Godden, M. Capel, J. E. P. Santos, M. W. Overton, and T. F. Duffield., 2012. Herd-level association of serum metabolites in the transition peri- od with disease, milk production, and early lactation reproductive performance. J. Dairy Sci.Journal of Dairy Science 95:5676–5682.

Domecq, J. J., Skidmore, A. L., Lloyd, J. W., and Kaneene, J. B., 1997. Relationship between body condition scores and conception at first artificial insemination in a large dairy herd of high yielding holstein cows. journal of dairy science, 80(1), 113–120.

Edmonson, A. J., Lean, I. J., Weaver, L. D., Farver, T., and Webster, G., 1989. A body condition scoring chart for holstein dairy cows. journal of dairy science, 72(1), 68–78.

Ferguson, J.D., Galligan, D.T. and Thomsen, N., 1994. Principal descriptors of body condition score in Holstein cows. *Journal of Dairy Science, 77*, 2695–2703.

Garnsworthy, P. C., 2007. Body Condition Score in Dairy Cows: Targets for Production and Fertility. Recent Advances in Animal Nutrition, 2006(1), 61–86.

Garnsworthy, P.C., 1988. The effect of energy reserves at calving on performance of dairy cows. In Nutrition and Lactation in the dairy cow. Ed. P.C. Garnsworthy, 157-170. Butterwords, London, UK.

Garnsworthy, P.C., and Jones, G.P., 1987. The influence of body condition at calving and dietary protein supply on voluntary food intake and performance in dairy cows. Animal Production, 44, 347-353.

Garnsworthy, P.C., and Topps, J.H., 1982. The effect of body condition score of dairy cows at calving on their food intake and performance when given complete diets. Animal Production, 35, 113-119.

Gillund, P., Reksen, O., Gröhn, Y. T., and Karlberg, K., 2001. Body condition related to ketosis and reproductive performance in Norwegian dairy cows. Journal of Dairy Science, 84(6), 1390–1396.

Gobikrushanth, M., Macmillan, K., Behrouzi, A., Hoff, B., Colazo, M.G., 2019. The factors associated with postpartum body condition score change and its relationship with serum analytes, milk production and reproductive performance in dairy cows. Livest. Sci. 228, 151–160. https://doi.org/10.1016/j.livsci.2019.05.016

Grainger, C., Wilhelms, G., and McGowan, A., 1982. Effect of body condition at calving and level of feeding in early lactation on milk production of dairy cows. Australian Journal of Experimental Agriculture, 22(115), 9.

Heuer, C., Schukken, Y. H., and Dobbelaar, P., 1999. Postpartum Body Condition Score and Results from the First Test Day Milk as Predictors of Disease, Fertility, Yield, and Culling in Commercial Dairy Herds. Journal of Dairy Science, 82(2), 295–304.

López-Gatius, F., Yániz, J., and Madriles-Helm, D., 2003. Effects of body condition score and score change on the reproductive performance of dairy cows: A meta-analysis. Theriogenology 59, 801–812. https://doi.org/10.1016/S0093-691X(02)01156-1

Lowman, B. G., Scott, N. A., and Somerville, S. H., 1976. Condition scoring of cattle. Edinburgh School Of Agriculture.

Manríquez, D., Thatcher, W.W., Santos, J.E.P., Chebel, R.C., Galvão, K.N., Schuenemann, G.M., Bicalho, R. C., Gilbert, R. O., Rodriguez-Zas, S., Seabury, C. M., Rosa, G. J. M., and Pinedo, P., 2021. Effect of body condition change and health status during early lactation on performance and survival of Holstein cows. Journal of Dairy ScienceVol. 104 12 12785–12799.

Marinho, M. N., Zimpel, R., Peñagaricano, F. and Santos, J. E. P., 2021. Assessing feed efficiency in early and mid lactation and its associations with performance and health in Holstein cows. Journal of Dairy Science 104:5493–5507. https://doi.org/10.3168/jds.2020-19652

Markusfeld, O., Galon, N., and Ezra, E., 1997. Body condition score, health, yield and fertility in dairy cows. Veterinary Record, 141(3), 67–72.

Middleton, E. L., Minela, T., and Pursley, J. R., 2019. The high-fertility cycle: How timely pregnancies in one lactation may lead to less body condition loss, fewer health issues, greater fertility, and reduced early pregnancy losses in the next lactation. Journal of Dairy Science, 102(6), 5577–5587.

Moore, S.M., DeVries, T.J., 2020. Effect of diet-induced negative energy balance on the feeding behavior of dairy cows. Journal of Dairy Science, 103 (8), 7288–7301.

Moreira, F., Risco, C., Pires, M. F. A., Ambrose, J. D., Drost, M., DeLorenzo, M., and Thatcher, W. W., 2000. Effect of body condition on reproductive efficiency of lactattng dairy cows receiving a timed insemination. Theriogenology, 53(6), 1305–1319.

Pedron, O., Cheli, F., Senatore, E., Baroli, D., and Rizzi, R., 1993. Effect of Body Condition Score at Calving on Performance, Some Blood Parameters, and Milk Fatty Acid Composition in Dairy Cows. Journal of Dairy Science, 76(9), 2528–2535.

Piantoni, P., VandeHaar, M.J., 2023. Symposium review: The impact of absorbed nutrients on energy partitioning throughout lactation. Journal of Dairy Science, 106 (3), 2167–2180.

Pryce, J. E., Coffey, M. P., and Brotherstone, S., 2000. The Genetic Relationship between Calving Interval, Body Condition Score and Linear Type and Management Traits in Registered Holsteins. Journal of Dairy Science, 83(11), 2664–2671.

Ribeiro, E. S., Lima, F. S., Greco, L. F., Bisinotto, R. S., Monteiro, A. P. A., Favoreto, M., Ayres, H., Marsola, R. S., Martinez, N., Thatcher, W. W., and Santos, J. E. P., 2013. Prevalence of periparturient diseases and effects on fertility of seasonally calving grazing dairy cows supplemented with concentrates. Journal of Dairy Science, 96(9), 5682–5697.

Roche, J. R., Macdonald, K. A., Burke, C. R., Lee, J. M., and Berry, D. P., 2007a. Associations Among Body Condition Score, Body Weight, and Reproductive Performance in Seasonal-Calving Dairy Cattle. Journal of Dairy Science, 90(1), 376–391.

Roche, J. R., Lee, J. M., Macdonald, K. A., and Berry, D. P., 2007b. Relationships Among Body Condition Score, Body Weight, and Milk Production Variables in Pasture-Based Dairy Cows. Journal of Dairy Science, 90(8), 3802–3815.

Ruegg, P.L., and Milton, R.L., 1995. Body Condition Scores of Holstein Cows on Prince-Edward-Island, Canada - Relationships with Yield, Reproductive-Performance, and Disease. J Dairy Sci 78, 552–564.

Santos, J.E., Rutigliano, H.M., and Sa Filho, M.F., 2009. Risk factors for resumption of postpartum estrous cycles and embryonic survival in lactating dairy cows. Anim Reprod Sci 110, 207–221. https://doi.org/10.1016/j.anireprosci.2008.01.014

Spoliansky, R., Edan, Y., Parmet, Y. and Halachmi, I., 2016. Development of automatic body condition scoring using a low-cost 3-dimensional Kinect camera. Journal of Dairy Science, 99, 7714–7725

Treacher, R.F., Reid, I.M., and Roberts, C.J., 1986. Effect of body condition at calving on the health and performance of dairy cows. Animal Production, 43, 1-6.

Waltner, S. S., McNamara, J. P., and Hillers, J. K., 1993. Relationships of Body Condition Score to Production Variables in High Producing Holstein Dairy Cattle. Journal of Dairy Science, 76(11), 3410–3419.