



Relationship of body weight at first calving with milk yield and herd life

L. Han,^{1*} A. J. Heinrichs,¹ A. De Vries,² and C. D. Dechow¹

¹Department of Animal Science, The Pennsylvania State University, University Park 16802

²Department of Animal Sciences, University of Florida, Gainesville 32611

ABSTRACT

The objectives of this study were to investigate the association of body weight (BW) at first calving (BWFC) and maturity rate (MR; BWFC as a percentage of mature BW) with first-lactation 305-d milk yield (FLMY), milk yield (MY) in the 24 mo following first calving (24MMY), herd life, and BW change (BWC) through the first month of lactation in Holstein heifers. We retrieved daily milk production records and daily BW records from AfiFarm (S. A. E. Afikim, Kibbutz Afikim, Israel). The data set included daily records for 1,110 Holstein cows from The Pennsylvania State University ($n = 435,002$ records) and 1,229 Holstein cows from University of Florida ($n = 462,013$ records) that calved from 2001 to 2016. Body weight at first calving was defined as mean BW from 5 to 10 d in milk of the first lactation, whereas BWC represented change from BWFC to average BW from 30 to 40 d in milk. First-lactation 305-d MY and 24MMY were analyzed with a linear model that included effects of farm-year-season of calving, age at calving, and quintiles of BWFC, MR, or BWC. Body weight change was analyzed with the same model to determine associations with BWFC. Survival analysis was performed to estimate the effect of BWFC on survival. Heifers in the top 60% of BWFC had significantly higher FLMY (10,041 to 10,084 kg) than lighter heifers (9,683 to 9,917 kg), but there was wide variation in every quintile, and no relationship of BWFC and FLMY existed within the top 60%. Relationships between BWFC and 24MMY were not significant. Heifers with higher BWFC or MR lost significantly more BW in early lactation. Although BWFC and MR were significant predictors of FLMY, they accounted for <3% of variation in FLMY or 24MMY, suggesting that BWFC and MR are not primary contributors to variation in MY. Compared with the lightest heifers, the heaviest heifers were 49% more likely to be culled at a given time. These data indicated that, among heifers

managed similarly, heavier heifers produced more milk in first lactation than lighter heifers but lost more BW, faced a higher risk of being culled, and did not produce more milk in the long term. Based on our data, heifers that reach between 73 and 77% MR at first calving can produce more milk in their first lactation without sacrificing long-term MY and herd life.

Key words: body weight, first calving, milk yield, herd life

INTRODUCTION

On an average dairy farm, heifer rearing accounts for 15 to 20% of total expenses (Gabler et al., 2000; Hutchison et al., 2017). Culling rate and age at first calving (AFC) were reported to be the most important factors that influenced heifer rearing cost (Tozer and Heinrichs, 2001). For a 100-cow dairy farm with 25% cull rate and average AFC of 25 mo, a 1-mo reduction in AFC resulted in a \$1,400 reduction in total heifer rearing costs (Tozer and Heinrichs, 2001).

The optimal AFC for Holstein cattle has traditionally been considered to be 24 mo (Ettema and Santos, 2004; Mohd Nor et al., 2013). However, the population trend over the past 30 yr has been to reduce AFC by 3 d/yr, and the net result at present is many heifers calving at 22 to 23 mo (Heinrichs et al., 2017). However, Hutchison et al. (2017) found that Holsteins first giving birth at 24 mo had higher first-lactation milk yield (FLMY) and lower long-term milk yield (MY) than those that first gave birth at 21 to 22 mo. Heifers that had lower AFC also had higher PTA of lifetime net merit, higher cow conception rate, and higher daughter pregnancy rate. These results could be interpreted to suggest that properly managed heifers can give birth 2 mo earlier while maintaining or improving productivity and profitability; alternatively, one could conclude that heifers that are genetically superior for fertility and lifetime net merit calve earlier and have higher long-term MY.

Body weight at first calving (BWFC) is another widely evaluated trait of heifer rearing. Previous studies have shown a small yet positive relationship between FLMY and BWFC (Heinrichs and Heinrichs, 2011).

Received July 3, 2020.

Accepted August 21, 2020.

*Corresponding author: cdd1@psu.edu

Previous studies also indicated that after a certain BW threshold, the MY return for increased BW starts to diminish. Keown and Everett (1986) suggested that 567 kg was the optimal prepartum BWFC for FLMY.

Relationships between BWFC and FLMY have been widely reported and suggest that higher BW is preferred. However, the proportion of FLMY differences explained by BWFC is generally not established. Additionally, relationships of BWFC with long-term MY and herd life (HL) are less documented. The objectives of the current study were to estimate the effect of BWFC and MR on MY, BW change (BWC), and HL in Holstein cattle and to analyze the proportion variation in MY variation explained by BWFC or MR in 2 experimental herds.

MATERIALS AND METHODS

Animals

Data included daily BW and MY from The Pennsylvania State University (PSU) and University of Florida (UF) dairy herds. The PSU dairy herd is located in State College, Pennsylvania, and the UF dairy herd is located in Alachua, Florida. For both herds, calves were housed separately until weaning. Heifers in the UF herd are housed outside until calving, whereas heifers in the PSU herd are mostly housed inside the barn, with pasture access during summer for bred heifers. Calves and heifers in both herds were fed following the NRC (2001) guidelines. Cows in both herds were fed a corn silage-based TMR and milked twice per day, and lactating cows were primarily housed in sand-bedded freestalls with fans and sprinklers for heat abatement; PSU also has a tiestall facility that is used primarily for nutrition trials for 60 cows.

Daily BW and MY were retrieved from the AfiFarm herd management system (S. A. E. Afikim, Kibbutz Afikim, Israel), and BW was recorded using the Afi-Weigh weighing system (S. A. E. Afikim). This system records the BW of every cow when it exits the milking parlor and then stores the mean of the morning and evening milkings as a single value. The final data set included records from 1,110 and 1,229 Holstein dairy heifers from the PSU and UF dairy herds, respectively. The PSU data were collected from August 2001 to December 2016, whereas the UF data were collected from August 2010 to December 2016.

Edits

The initial number of records of BW and MY from PSU and UF and the records removed by edits are shown in Table 1. The BW and MY records of heifers

that began milking younger than 20 mo were removed because neither herd intentionally inseminates heifers to calve before 20 mo, and records after 305 DIM were removed for evaluation of first-lactation yield. Most records from heifers calving before 20 mo were from a study at PSU where heifers were induced into lactation at 14 or 18 mo of age (Macrina et al., 2014). The number of BW records available for each animal in early lactation depended on how long the animal was milking before their electronic identification leg bands were applied, management protocols that allow first-lactation heifers to bypass the weigh scale to avoid additional stress during initial milkings, and occasional scale malfunction; these factors varied by herd and time. The following edits were implemented to include as many animals as possible but require that each had enough data to accurately derive postpartum BW: animals were required to have at least 10 BW records in the first 30 DIM, 7 BW records in the first 14 DIM, or 3 BW records in the first 7 DIM for first lactation. To identify and eliminate outlier data points, we used PROC MIXED of SAS (version 9.4; SAS Institute Inc., Cary, NC) to generate curves of BW and MY. Separate curves were fit by cow and lactation with fourth-order polynomials of DIM. A BW or MY record was set to missing if it was more than 3 standard deviations away from the predicted value.

We used ASReml (Gilmour et al., 2015) to generate lactation MY and BW curves for each cow and lactation, with a model that included the fixed effects of intercept, lactation group ($n = 1, 2, \geq 3$), and biweekly DIM classes within lactation group; random effects were cow within lactation and date within herd. Solutions were then used to fill in dates with missing values and to extrapolate first lactations that were less than 305 d. Predicted daily MY was derived as overall mean + lactation group effect + biweekly DIM within lactation effect + cow within lactation effect + date effect. Overall, 1.4% of the total daily MY records used in this study were predicted values, of which 0.6% were for missing records and 0.8% were for extrapolation to

Table 1. Number of initial daily milk records and the number lost and generated during data edits for The Pennsylvania State University (PSU) and University of Florida (UF) dairy herds

Data step	PSU	UF
Initial file	523,846	604,431
Age <20 mo	1,306	13
Milk yield outliers	14,719	21,768
Insufficient number of records in first 30 DIM	78,706	127,517
Total records deleted	94,731	149,298
Daily milk records remaining after edits	429,115	455,133
Predicted milk yield records	5,887	6,880
Total records	435,002	462,013

305-d yield. Likewise, predicted daily BW from DIM 5 to DIM 10 was substituted for missing values for cows that satisfied the previously specified requirement for number of BW records.

Five BW values were calculated: (1) BWFC, which was the mean BW from DIM 5 to DIM 10 after first calving; (2) BW2, which was the mean BW from DIM 30 to DIM 40 after first calving; (3) BWC, which was calculated as $[(BWFC - BW2)/BWFC] \times 100$; (4) mature calving BW (MBW), which was the cow's mean BW from DIM 5 to DIM 10 of their third lactation; and (5) MR, which was calculated as $(BWFC/MBW) \times 100$.

Two MY values were calculated: FLMY, which was considered a shorter-term measure of yield, and total MY in the 24 mo after first calving (**24MMY**), which was considered a longer-term indicator of MY. The FLMY was the sum of a heifer's daily MY from DIM 5 to 305 of first lactation, and 24MMY was the sum of daily MY from DIM 5 of first lactation to 730 d (24 mo) after first calving. We used 24MMY instead of lifetime MY because many animals still in the herd would have censored lifetime records and because the period was long enough to capture the ability of a cow to successfully complete 2 lactation cycles. Animals that were still alive at the end of the data sampling period (December 31, 2016) and that had an HL of <730 d were excluded from 24MMY analysis; HL was the number of days between a heifer's first calving to the date of their last MY record. Cows with at least 1 milking record within the last 2 mo of the sampling period (November and December of 2016) were considered alive.

Milk Production Analysis

Data analysis was performed with PROC GLM of SAS using the following model:

$$y_{ijk} = FYS_i + AFC_j + Q_k + e_{ijk},$$

where y was the dependent variables of FLMY, 24MMY, and BWC; FYS was the fixed effect of farm-year-season of calving i , where seasons were defined as January to March, April to June, July to September, and October to December; AFC was the fixed effect of AFC in months j (20 to 38); Q was the k quintiles (1 to 5) of BWFC, BWC, or MR nested within a farm-year; and e was the random residual. Least square means were generated for Q , and differences were determined using a Tukey adjustment.

Coefficients of partial determination (partial R^2) were determined for BWFC, BWC, and MR to demonstrate the amount of variation in FLMY, 24MMY, or BWC explained by quintiles. To calculate partial R^2 , type

III sums of squares for the quintile effect were divided by total sums of squares minus the farm-year-season of calving and age type III sums of squares. Variation among animals within a quintile could be masked to some degree by grouping animals together; therefore, partial R^2 was also derived from models where quintile was replaced with fourth-order polynomials of the trait. Fourth-order polynomials of BWFC were significant for the analysis of FLMY and so were applied to each trait for consistency.

Survival Analysis

Survival analysis was used to investigate the relationship between HL and BWFC or MR with PROC PHREG of SAS 9.4. Survival time was HL from 5 d after first calving through culling or the end of the data sampling period (December 31, 2016). The animals were categorized as alive if they had at least 1 milking record within the last 2 mo of the sampling period (November and December of 2016). The model included fixed effects of farm-year-season of calving, AFC, and quintiles of BWFC, with those categorized as alive (29.6%) considered censored.

RESULTS

The heifers from PSU calved for the first time at 24.7 ± 2.5 mo, weighed 547 ± 54 kg after first calving, produced $10,350 \pm 1,631$ kg of milk in their first lactation, and produced $18,138 \pm 6,563$ kg of milk through 24 mo after first calving, and 62% of the cows survived to 24 mo after first calving. Heifers from UF gave birth at 23.0 ± 1.8 mo, weighed 535 ± 48 kg after first calving, produced $8,818 \pm 1,430$ kg of milk in their first lactation, and produced $14,576 \pm 5,260$ kg of milk through 24 mo after first calving, and 57% of the cows survived to 24 mo after first calving. Of cows that had the opportunity to survive through at least their fifth lactation before the end of our data collection period, cows were in the lactating herd for 851 and 802 d for PSU and UF herds, respectively; this corresponds to approximately 2.8 and 2.6 305-d lactations. The national average record equivalent is 2.78 lactations (VanRaden, 2018), indicating that survival in both herds was similar to the national average. Descriptive statistics of the 2 herds are presented in Table 2.

Means, standard deviations, and the number of excluded animals for BWFC, BWC, and MR of each quintile are shown in Table 3. For the PSU herd, average BWFC ranged from 477 ± 24 kg (quintile 1) to 624 ± 35 kg (quintile 5), average BWC ranged from $-1.60 \pm 2.88\%$ (quintile 1) to $8.32 \pm 3.71\%$ (quintile 5), and average MR ranged from $68.95 \pm 3.27\%$ (quintile 1) to

Table 2. Descriptive statistics for The Pennsylvania State University (PSU) and University of Florida (UF) dairy herds

Trait ¹	PSU			UF		
	No.	Mean	SD	No.	Mean	SD
AFC, mo	1,110	24.7	2.5	1,229	23.0	1.8
FLMY, kg	1,110	10,350	1,631	1,229	8,818	1,430
24MMY, kg	979	18,138	6,563	919	14,576	5,260
BWFC, kg	1,110	547	54	1,229	535	48
BW2, kg	1,110	530	53	1,229	520	46
BWC, %	1,110	3.03	3.97	1,229	2.68	3.85
MBW, kg	429	701	68	399	690	61
MR, %	429	77.69	7.00	399	76.60	6.62
24MS, %		62			57	
Censored, %		18			40	

¹AFC = age at first calving; FLMY = first-lactation 305-d milk yield; 24MMY = 24-mo milk yield; BWFC = first-lactation postpartum BW; BW2 = first-lactation 1-mo postpartum BW; BWC = BW change through first month of lactation; MBW = mature postpartum BW; MR = BW mature rate; 24MS = percentage of cows survived to 24 mo after first calving; Censored = percentage of cows remaining in the herd at the end of the data collection period.

87.91 ± 5.55% (quintile 5). For the UF herd, average BWFC ranged from 473 ± 21 kg (quintile 1) to 604 ± 28 kg (quintile 5), average BWC ranged from -2.47 ± 2.42% (quintile 1) to 7.85 ± 2.49% (quintile 5), and average MR ranged from 67.83 ± 2.76% (quintile 1) to 85.97 ± 3.91% (quintile 5).

Effect of BWFC

Least squares means of FLMY, BWC, and 24MMY for each BWFC quintile group are shown in Table 4. For FLMY, heifers in quintiles 3 to 5 of BWFC pro-

duced more milk in their first lactation (≥10,041 kg; $P < 0.05$) than heifers in quintiles 1 and 2 (≤9,917 kg).

Our analysis showed that heavier heifers lost more BW during the first month of lactation (larger BWC) than lighter heifers. Heifers in BWFC quintiles 4 and 5 lost the most BW during the first month of lactation (BWC ≥3.48%). Heifers in BWFC quintile 1 gained BW during the first month of lactation (BWC = -1.74%). Heifers in quintiles 2 and 3 had 2.74 and 3.38% BWC, respectively, during the first month of lactation, which was different ($P < 0.05$) from heifers in heavier quintiles and lighter quintiles.

Table 3. Number of observations for first-lactation milk yield (N1) and 24-mo milk yield (N24), means, and SD by quintile (Q) for The Pennsylvania State University (PSU) and University of Florida (UF) dairy herds

Item ¹	PSU				UF			
	N1	Mean	SD	N24	N1	Mean	SD	N24
BWFC, kg								
Q1	217	477	24	203	244	473	21	219
Q2	225	517	14	214	247	508	15	221
Q3	224	544	14	213	248	532	14	223
Q4	225	572	17	213	247	559	15	222
Q5	219	624	35	207	243	604	28	218
MR, %								
Q1	82	68.95	3.27		77	67.83	2.76	
Q2	88	73.60	2.47		81	72.87	1.83	
Q3	87	76.85	2.48		81	76.41	1.93	
Q4	88	81.01	2.88		81	79.73	1.94	
Q5	84	87.91	5.55		79	85.97	3.91	
BWC, %								
Q1	217	-1.60	2.88	205	244	-2.47	2.42	218
Q2	225	1.42	0.98	213	247	0.90	1.01	222
Q3	224	2.72	0.93	212	247	2.65	0.85	221
Q4	225	4.28	1.52	213	247	4.49	1.11	222
Q5	219	8.32	3.71	207	244	7.85	2.49	219

¹BWFC = first-lactation postpartum BW; MR = maturity rate; BWC = BW change.

Table 4. Least squares means for first-lactation milk yield (FLMY), percent BW change through the first month of lactation (BWC), and milk yield in the 24 mo after first calving (24MMY) by BW at first calving (BWFC) quintile, with full model R^2 , partial R^2 due to BWFC quintile (Q R^2), and partial R^2 due to BWFC polynomial (PL R^2)

Item	FLMY, kg		BWC, %		24MMY, kg	
	Mean	SE	Mean	SE	Mean	SE
BWFC quintile						
1	9,683 ^a	163	-1.74 ^a	0.18	15,306	644
2	9,917 ^a	159	2.74 ^b	0.17	15,391	625
3	10,041 ^b	158	3.38 ^b	0.18	15,278	621
4	10,084 ^b	156	3.48 ^c	0.18	15,507	610
5	10,034 ^b	150	3.60 ^c	0.19	15,092	587
R^2	0.34		0.21		0.30	
Q R^2	0.01		0.03		<0.01	
PL R^2	0.02		0.03		0.02	

^{a-c}Different superscripts within a column indicate a significant difference ($P < 0.05$).

Body weight at first calving had no statistically significant effect on 24MMY. Numerically, the heaviest heifers (quintile 5) produced the least amount of milk (15,092 kg) during the first 24 mo of their HL.

The R^2 of the full models was 0.34, 0.21, and 0.30 for the FLMY, BWC, and 24MMY analyses, respectively. The partial R^2 due to BWFC quintile was 0.01, 0.03, and <0.01 for the FLMY, BWC, and 24MMY analyses, respectively. The partial R^2 due to BWFC polynomial was 0.02, 0.03, and 0.02 for the FLMY, BWC, and 24MMY analyses, respectively. These results indicated that most of the variance in short-term and longer-term MY and in BWC were explained by the farm-year-season and AFC effects.

Effect of MR

Least squares means for FLMY and BWC for each MR quintile group are shown in Table 5. We did not consider 24MMY because cows culled before they

Table 5. Least squares means for first-lactation milk yield (FLMY) and percent BW change through the first month of lactation (BWC) by maturity rate (MR) quintile, with full model R^2 , partial R^2 due to MR quintile (Q R^2), and partial R^2 due to MR polynomial (PL R^2)

Item	FLMY, kg		BWC, %	
	Mean	SE	Mean	SE
MR quintile				
1	9,799 ^a	189	2.34 ^a	0.30
2	9,892 ^a	182	2.89 ^a	0.29
3	10,147 ^a	186	2.93 ^a	0.29
4	10,270 ^b	182	3.65 ^b	0.30
5	10,203 ^a	173	3.99 ^b	0.31
R^2	0.35		0.26	
Q R^2	0.02		0.02	
PL R^2	0.01		0.03	

^{a,b}Different superscripts within a column indicate a significant difference ($P < 0.05$).

reached maturity do not have MR. Higher MR was associated with heifers that were more mature at first calving relative to third calving. For FLMY, heifers in quintile 4 of MR produced more milk in their first lactation (10,270 kg; $P < 0.05$) than those in other quintiles. Higher MR was also associated with greater ($P < 0.05$) BW loss after first calving, as heifers in MR quintiles 4 and 5 lost more BW during the first month of lactation ($BWC \geq 3.65\%$) than heifers in MR quintiles 1 to 3 ($BWC \leq 2.93\%$).

The R^2 of the full model was 0.35 for FLMY and 0.26 for BWC analyses. The partial R^2 due to MR ranged from 0.01 to 0.03.

Effect of BWC

Least squares means of FLMY and 24MMY for each BWC quintile group are shown in Table 6. Heifers in quintiles 4 and 5 of BWC (lost more BW in the first month of first lactation) produced more milk in their first lactation ($\geq 10,114$ kg; $P < 0.05$) than heifers in other quintiles. Heifers in quintiles 1 and 2 of BWC (lost less BW in the first month of first lactation) produced less milk in their first lactation ($\leq 9,832$ kg; $P < 0.05$).

Similar to BWFC, BWC had no effect ($P > 0.10$) on heifer 24MMY. The R^2 of the full model was 0.43 for FLMY and 0.30 for 24MMY analyses. The partial R^2 due to BWC quintile was 0.02 for FLMY and <0.01 for 24MMY analyses. The partial R^2 due to BWC polynomial was 0.03 and <0.01 for the FLMY and 24MMY analyses, respectively.

Survival Analysis

The results of survival analysis of different BWFC and MR quintiles are shown in Table 7 and Table 8, respectively. When compared with the lightest heifers

Table 6. Least squares means for first-lactation milk yield (FLMY) and milk yield in the 24 mo after first calving (24MMY) by BW change (BWC) quintile, with full model R^2 , partial R^2 due to BWC quintile (Q R^2), and partial R^2 due to BWC polynomial (PL R^2)

Item	FLMY, kg		24MMY, kg	
	Mean	SE	Mean	SE
BWC quintile				
1	9,641 ^a	156	14,655	617
2	9,832 ^a	155	15,105	609
3	10,059 ^b	156	15,453	618
4	10,114 ^c	155	15,011	608
5	10,243 ^c	153	15,800	599
R^2	0.43		0.30	
Q R^2	0.02		<0.01	
PL R^2	0.03		<0.01	

^{a-c}Different superscripts within a column indicate a significant difference ($P < 0.05$).

(BWFC quintile 1), heifers in quintiles 2, 3, 4, and 5 were 14, 22, 18, and 49% more likely to be culled at any given time, respectively. The raw number of average days in the milking herd declined from 877 d in quintile 1 to 768 d in quintile 5 in accordance with higher culling risk for heavier heifers. Likewise, the least mature heifers had the lowest risk of culling; heifers in quintiles 2, 3, 4, and 5 faced 15, 33, 50, and 50% higher risk of being culled at any given time point relative to quintile 1, respectively.

DISCUSSION

Previous studies have shown a positive relationship between MY and BWFC (Keown and Everett, 1986; Van Amburgh et al., 1998; Handcock et al., 2019). Our current study showed a similar trend, which is that heavier heifers tended to produce more milk in their first lactation than lighter heifers but that there is a point at which additional BW (BWFC quintile >3) is not associated with further increases in MY. The poten-

Table 7. Hazard ratios and the 95% CI of each quintile of BW at first calving (BWFC)

BWFC quintile	Hazard ratio ¹	
	Mean	95% CI
1	1.00 ^a	Referent
2	1.14 ^a	0.97–1.34
3	1.22 ^b	1.04–1.44
4	1.18 ^b	1.00–1.39
5	1.49 ^c	1.27–1.75

^{a-c}Different superscripts within a column indicate a significant difference ($P < 0.05$).

¹Hazard ratio was defined as the risk of being culled relative to quintile 1.

Table 8. Hazard ratios and the 95% CI of each quintile of maturity rate (MR)

MR quintile	Hazard ratio ¹	
	Mean	95% CI
1	1.00 ^a	Referent
2	1.15 ^{ab}	0.87–1.52
3	1.33 ^b	1.00–1.76
4	1.50 ^c	1.14–1.99
5	1.50 ^c	1.13–1.98

^{a-c}Different superscripts within a column indicate a significant difference ($P < 0.05$).

¹Hazard ratio was defined as the risk of being culled relative to quintile 1.

tial physiological reasons for this trend are that lighter heifers need to partition additional nutrient intake to support their own growth instead of producing milk and that their intakes are less (NRC, 2001). This was supported by our observations that the lightest heifers gained 1.74% BW during the first month of lactation, whereas the heaviest heifers lost the most BW (3.60%).

Previous research reports conflicting results about the relationship between BWFC and long-term MY. Heinrichs and Heinrichs (2011) suggested that BWFC had no effect on long-term MY using a smaller data set. Handcock et al. (2019) showed that there was a significant curvilinear relationship between BWFC and long-term MY, with MY through 3 lactations peaking for heifers that were 565 kg at 21 mo of age. The relationship between BWFC and long-term MY in the current study was generally inconsistent and not significant. The partial R^2 analysis indicated that, after accounting for farm-year-season of calving and AFC effects, BWFC explained a very small amount of the remaining variance of FLMY, 24MMY, and BWC.

Heifer growth rates were reported to have a significant effect on heifers' future production performance, but the effects were mixed (Lammers et al., 1999; Heinrichs et al., 2017). Lammers et al. (1999) reported that heifers with higher prepubertal growth rate produced less milk in their first lactation compared with a control group. However, Zanton and Heinrichs (2005) found a quadratic relationship between heifers' prepubertal growth and milk production; they suggested that the optimal ADG for heifers in their data set was 799 g/d before puberty. Hoffman (1997) found that accelerated postpubertal growth resulted in slightly smaller postpartum BW and lower first-lactation production. These animals were also younger at calving.

The current study demonstrated that, after calving, the heaviest heifers were 49% more likely to be culled at any given time than the lightest heifers. Zavadilová et al. (2011) showed that in a population containing

116,369 Czech Holstein cows, increased body size indicators (stature, chest width, body depth, and height at the sacrum) all had negative associations with cow longevity. Hansen et al. (1999) reported that compared with the large body size genetic line, cows in the small line had smaller BW, body dimensions, and birth weight but did not differ for MY. Cows in the small line had 87.7 d (15.4%) longer productive life than cows in the large line. Tsuruta et al. (2004) found negative genetic correlation between productive life and body size composite.

Some of the unfavorable relationship of BW to HL may result from the effects of early-lactation BW loss. Body weight had a strong genetic correlation (0.60) with BCS in a previous analysis of PSU records, and BWC is an indicator of change in BCS and energy balance (Toshniwal et al., 2008). Negative energy balance during the early-lactation period is reported to have unfavorable relationships with reproduction (Nebel and McGilliard, 1993). High BW may be associated with high BCS and place heifers at risk of excessive body condition mobilization postcalving. However, other studies have indicated that underconditioned heifers also have poor reproductive outcomes. A recent study reported an intermediate optimum for the relationship of BW at 15 mo of age with the proportion of animals that calved within the subsequent calving window (Handcock et al., 2020). Cows genetically inclined toward low BW during peak lactation also have poorer fertility due to an inability to maintain body condition (Pryce et al., 2001; Frigo et al., 2010).

CONCLUSIONS

Our study showed that among cohorts of heifers managed similarly, heifers that were heavier at first calving produced somewhat more milk in their first lactation than lighter heifers. Heifers that were heavier at calving also lost more weight during the first month of lactation and subsequently faced higher risk of being culled earlier in life than lighter heifers. Based on our data, heifers that reach between 73 and 77% MR at first calving can produce more milk in their first lactation without sacrificing long-term MY and HL.

ACKNOWLEDGMENTS

This research was a component of NC-2042: Management Systems to Improve the Economic and Environmental Sustainability of Dairy Enterprises. We thank Alltech Inc. (Nicholasville, KY) for providing the salary for L. Han. We also acknowledge the farm staff of each

university for the collection and upkeep of farm records. The authors have not stated any conflicts of interest.

REFERENCES

- Ettema, J. F., and J. E. P. Santos. 2004. Impact of age at calving on lactation, reproduction, health, and income in first-parity Holsteins on commercial farms. *J. Dairy Sci.* 87:2730–2742. [https://doi.org/10.3168/jds.S0022-0302\(04\)73400-1](https://doi.org/10.3168/jds.S0022-0302(04)73400-1).
- Frigo, E., C. D. Dechow, O. Pedron, and B. G. Cassell. 2010. The genetic relationship of body weight and early-lactation health disorders in two experimental herds. *J. Dairy Sci.* 93:1184–1192. <https://doi.org/10.3168/jds.2009-2313>.
- Gabler, M. T., P. R. Tozer, and A. J. Heinrichs. 2000. Development of a cost analysis spreadsheet for calculating the costs to raise a replacement dairy heifer. *J. Dairy Sci.* 83:1104–1109. [https://doi.org/10.3168/jds.S0022-0302\(00\)74975-7](https://doi.org/10.3168/jds.S0022-0302(00)74975-7).
- Gilmour, A. R., B. J. Gogel, B. R. Cullis, S. J. Welham, and R. Thompson. 2015. ASReml User Guide Release 4.1. VSN Int. Ltd., Hemel Hempstead, UK.
- Handcock, R. C., N. Lopez-Villalobos, L. R. McNaughton, P. J. Back, G. R. Edwards, and R. E. Hickson. 2019. Positive relationships between body weight of dairy heifers and their first-lactation and accumulated three-parity lactation production. *J. Dairy Sci.* 102:4577–4589. <https://doi.org/10.3168/jds.2018-15229>.
- Handcock, R. C., N. Lopez-Villalobos, L. R. McNaughton, P. J. Back, G. R. Edwards, and R. E. Hickson. 2020. Body weight of dairy heifers is positively associated with reproduction and stayability. *J. Dairy Sci.* 103:4466–4474. <https://doi.org/10.3168/jds.2019-17545>.
- Hansen, L. B., J. B. Cole, G. D. Marx, and A. J. Seykora. 1999. Productive life and reasons for disposal of Holstein cows selected for large versus small body size. *J. Dairy Sci.* 82:795–801. [https://doi.org/10.3168/jds.S0022-0302\(99\)75298-7](https://doi.org/10.3168/jds.S0022-0302(99)75298-7).
- Heinrichs, A. J., and B. S. Heinrichs. 2011. A prospective study of calf factors affecting first-lactation and lifetime milk production and age of cows when removed from the herd. *J. Dairy Sci.* 94:336–341. <https://doi.org/10.3168/jds.2010-3170>.
- Heinrichs, A. J., G. I. Zanton, G. J. Lascano, and C. M. Jones. 2017. A 100-year review: A century of dairy heifer research. *J. Dairy Sci.* 100:10173–10188. <https://doi.org/10.3168/jds.2017-12998>.
- Hoffman, P. C. 1997. Optimum body size of Holstein replacement heifers. *J. Anim. Sci.* 75:836–845. <https://doi.org/10.2527/1997.753836x>.
- Hutchison, J. L., P. VanRaden, D. Null, J. Cole, and D. Bickhart. 2017. Genomic evaluation of age at first calving. *J. Dairy Sci.* 100:6853–6861. <https://doi.org/10.3168/jds.2016-12060>.
- Keown, J. F., and R. W. Everett. 1986. Effect of days carried calf, days dry, and weight of first calf heifers on yield. *J. Dairy Sci.* 69:1891–1896. [https://doi.org/10.3168/jds.S0022-0302\(86\)80615-4](https://doi.org/10.3168/jds.S0022-0302(86)80615-4).
- Lammers, B. P., A. J. Heinrichs, and R. S. Kensing. 1999. The effects of accelerated growth rates and estrogen implants in prepubertal Holstein heifers on estimates of mammary development and subsequent reproduction and milk production. *J. Dairy Sci.* 82:1753–1764. [https://doi.org/10.3168/jds.S0022-0302\(99\)75406-8](https://doi.org/10.3168/jds.S0022-0302(99)75406-8).
- Macrina, A. L., A. C. W. Kauf, D. A. Pape-Zambito, and R. S. Kensing. 2014. Induced lactation in heifers: Effects of dexamethasone and age at induction on milk yield and composition. *J. Dairy Sci.* 97:1446–1453. <https://doi.org/10.3168/jds.2013-7241>.
- Mohd Nor, N., W. Steeneveld, T. van Werven, M. C. M. Mourits, and H. Hogeveen. 2013. First-calving age and first-lactation milk production on Dutch dairy farms. *J. Dairy Sci.* 96:981–992. <https://doi.org/10.3168/jds.2012-5741>.
- Nebel, R. L., and M. L. McGilliard. 1993. Interactions of high milk yield and reproductive performance in dairy cows. *J. Dairy Sci.* 76:3257–3268.
- NRC. 2001. Nutrient Requirements of Dairy Cattle. 7th rev. ed. National Academies Press, Washington, DC.

- Pryce, J. E., M. P. Coffey, and G. Simm. 2001. The relationship between body condition score and reproductive performance. *J. Dairy Sci.* 84:1508–1515. [https://doi.org/10.3168/jds.S0022-0302\(01\)70184-1](https://doi.org/10.3168/jds.S0022-0302(01)70184-1).
- Toshniwal, J. K., C. D. Dechow, B. G. Cassell, J. A. D. R. N. Apuhamy, and G. A. Varga. 2008. Heritability of electronically recorded daily body weight and correlations with yield, dry matter intake, and body condition score. *J. Dairy Sci.* 91:3201–3210. <https://doi.org/10.3168/jds.2007-0627>.
- Tozer, P. R., and A. J. Heinrichs. 2001. What affects the costs of raising replacement dairy heifers: A multiple-component analysis. *J. Dairy Sci.* 84:1836–1844. [https://doi.org/10.3168/jds.S0022-0302\(01\)74623-1](https://doi.org/10.3168/jds.S0022-0302(01)74623-1).
- Tsuruta, S., I. Misztal, and T. J. Lawlor. 2004. Genetic correlations among production, body size, udder, and productive life traits over time in Holsteins. *J. Dairy Sci.* 87:1457–1468. [https://doi.org/10.3168/jds.S0022-0302\(04\)73297-X](https://doi.org/10.3168/jds.S0022-0302(04)73297-X).
- Van Amburgh, M. E., D. M. Galton, D. E. Bauman, R. W. Everett, D. G. Fox, L. E. Chase, and H. N. Erb. 1998. Effects of three prepubertal body growth rates on performance of Holstein heifers during first lactation. *J. Dairy Sci.* 81:527–538. [https://doi.org/10.3168/jds.S0022-0302\(98\)75604-8](https://doi.org/10.3168/jds.S0022-0302(98)75604-8).
- VanRaden, P. M. 2018. Net merit as a measure of lifetime profit: 2018 revision. Accessed Dec. 8, 2020. <https://aipl.arsusda.gov/reference/nmcalc-2018.htm>.
- Zanton, G. I., and A. J. Heinrichs. 2005. Meta-analysis to assess effect of prepubertal average daily gain of Holstein heifers on first-lactation production. *J. Dairy Sci.* 88:3860–3867. [https://doi.org/10.3168/jds.S0022-0302\(05\)73071-X](https://doi.org/10.3168/jds.S0022-0302(05)73071-X).
- Zavadilová, L., E. Němcová, and M. Štípková. 2011. Effect of type traits on functional longevity of Czech Holstein cows estimated from a Cox proportional hazards model. *J. Dairy Sci.* 94:4090–4099. <https://doi.org/10.3168/jds.2010-3684>.

ORCIDS

- L. Han  <https://orcid.org/0000-0002-6646-3134>
 A. J. Heinrichs  <https://orcid.org/0000-0001-5217-473X>
 A. De Vries  <https://orcid.org/0000-0003-4511-0388>
 C. D. Dechow  <https://orcid.org/0000-0002-9012-2807>