Relationships Among Body Condition Score, Body Weight, and Milk Production Variables in Pasture-Based Dairy Cows

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ABSTRACT

The objective of the present study was to identify and quantify relationships among dairy cow body condition score (BCS) and body weight (BW) and production variables in pasture-based, seasonal-calving herds. More than 2,500 lactation records from 897 spring-calving Holstein-Friesian and Jersey dairy cows were used in the analyses. Six variables related to BCS and BW, including observations precalving, at calving, and nadir as well as days to nadir and change precalving and between calving and nadir were generated. An exponential function was fitted within lactation to milk and 4% fat-corrected milk (FCM) yield data to model lactation curves. The milk production variables investigated were the parameters of the fitted function as well as accumulated yield of milk and FCM at 60 and 270 days in milk and average milk composition. Mixed models were used to identify BCS and BW variables that significantly affected milk production. After adjusting for the fixed effect of year of calving, parity, and days dry, milk and FCM yields were nonlinearly associated with calving and nadir BCS, increasing at a declining rate up to BCS 6.0 to 6.5 (10-point scale; approximately 3.5 in the 5-point scale) and declining thereafter. However, there was very little increase in milk and FCM yields above a calving BCS of 5.0 (approximately 3.0 in the 5-point scale). Average milk fat content over 60 and 270 days in milk was positively correlated with increasing calving and nadir BCS. In comparison, milk protein percentage was not influenced by calving BCS but was positively associated with nadir BCS and negatively associated with BCS lost between calving and nadir. The effect of BW and changes in BW were similar to the effect of BCS, although the scale of the effect was breed-dependent. For example, milk and FCM yield increased linearly with increasing calving BCS, but the effect was greater

in Holstein-Friesians compared with Jersey cows. The results are consistent with the literature and highlight the important role that BCS and BW loss has on milk production, irrespective of the system of farming.

Key words: body condition score, milk, fitted function, pasture

INTRODUCTION

Several studies have quantified the effect of BCS, BW, and change in these variables throughout lactation on dairy cow health (Markusfeld et al., 1997; Roche and Berry, 2006; Berry et al., 2007) and reproduction (Domecq et al., 1997b; Beam and Butler, 1999; Buckley et al., 2003; Roche et al., 2007), acknowledging the importance of these measurable characteristics in dairy farm management. A general tendency has been shown across studies toward an improvement in the nonproduction-related traits with increased calving BCS and through less BCS and BW loss in early lactation, although the effect was likely quadratic (Roche et al., 2007).

Despite the effect of energy balance on health and reproduction, until recently, most dairy cattle breeding programs selected aggressively for increased milk production (Miglior et al., 2005), without much consideration for traits other than production. This has resulted in a cow that readily mobilizes condition to support lactation (homeorhesis; Bauman and Currie, 1980; Roche et al., 2006), only regaining lost condition when energy surplus to milk production, maintenance, and pregnancy is consumed. This relationship between BCS and milk production is consistent with fitted functions presented by Roche et al. (2006), which depicted BW and BCS profiles as mirror images of the lactation profile. Energy stores are therefore a key component of milk production.

Studies over 30 yr have evaluated the association between BCS and milk yield (see review by Broster and Broster, 1998), but results have been inconsistent. Many studies have identified a positive effect of either calving BCS (Grainger and McGowan, 1982; Waltner

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et al., 1993) or amount of BCS lost postpartum (Waltner et al., 1993; Ruegg and Milton, 1995) on milk production. Referring to research undertaken in the mid-1970s, Grainger and McGowan (1982) reported an increase in milk fat production (7.5 ± 3.5 kg) equivalent to 187 kg of FCM for each BCS unit increase between 3 and 6 at calving (1 to 8 scale; approximately 2.0 to 3.5 on a 5-point scale; Roche et al., 2004). This response is consistent with the results of Waltner et al. (1993), who reported a 322-kg increase in milk yield to 90 DIM by increasing calving BCS from 2.0 to 3.0 (5-point scale). In comparison, a large body of research in the United Kingdom (Garnsworthy and Topps, 1982a,b; Garnsworthy and Jones, 1987, 1993) identified no discernible effect of calving BCS on milk production.

The majority of research undertaken in grazing systems has reported a positive association between calving BCS and milk production (Stockdale 2004a,b, 2005; Roche et al., 2005). However, these studies were undertaken with small numbers of cows and examined only 2 or 3 BCS points and so do not enable the accurate determination of an optimum calving BCS for grazing systems.

In addition, although BCS has been the subject of considerable research, little has been reported about the relationship between BW and postpartum BW change on milk production. The objective nature of the BW measurement and the ability to automate its capture on farm make BW a potentially important management tool should associations be significant. Significant associations have been reported between BW and BW change and fertility (Roche et al., 2007), health (Berry et al., 2007), and milk production (Sieber et al., 1988; Hristov et al., 2005). An understanding of the effect of BW on milk production under grazing systems could be useful in making management decisions. Although there is a moderate correlation between BCS and BW ($r = 0.55$; Berry et al., 2006), associations between BW and milk yield are unlikely to be the same as between BCS and milk yield, because BW is also associated with maintenance requirements (a greater BW requiring more energy for maintenance), and BW change is often attenuated due to changes in gastrointestinal fill postcalving (NRC, 2001).

Considering the quadratic nature of the milk production response to calving BCS reported by Waltner et al. (1993) for cows consuming a TMR and the quadratic nature of the effect of BCS on health and production (Roche and Berry, 2006; Roche et al., 2007), defining the milk production response to BCS and BCS change in grazing systems is imperative to enable defining an economic optimum. The objective of this study was to quantify the direction and strength of the associations

among BCS, BW, and milk production under a compact seasonal-calving, pasture-based system of milk production.

MATERIALS AND METHODS

Data Available

The data set used in the present study, as well as a description of the research farm where all data were recorded, has previously been described in detail by Roche et al. (2007) and Berry et al. (2007). In summary, data on cow number, year of birth, parity number, and associated calving dates were extracted from the Dexcel research database on 2,635 lactations from 897 cows. Of the 897 cows, 374 were Jersey, and the remainder were Holstein-Friesian. All cows resided at No. 2 Dairy, Dexcel, Hamilton, New Zealand, from 1986 to 2000, inclusive.

Individual milk yields were recorded weekly, and milk fat, CP, and lactose concentrations of the milk were determined by Milkoscan (Foss Electric, Hillerød, Denmark) on the individual evening and morning aliquot samples collected on that day. Body condition score and BW were assessed within 1 wk of calving and every 2 wk during the intercalving period following the morning milking. Body condition score was assessed by palpating individual body parts and an average score recorded on a 10-point scale, in which 1 is emaciated and 10 is obese (Roche et al., 2004). The anatomical regions palpated included the thoracic and vertebral region of the spinal column (chine, loin, and rump), the ribs, the spinous processes (loin), the tuber sacrale (hip or hook bones), the tuber ischii (pin bones), the anterior coccygeal vertebrae (tail head), and the thigh region (Roche et al., 2004). Across the entire period of the study, only 4 trained personnel assessed BCS on all animals. Furthermore, all of these assessors were trained by 1 individual. Body weight was measured using a calibrated electronic scale (Tru-Test, Auckland, New Zealand). In total, 95,971 milk test-day records, 68,986 BCS records, and 68,980 BW records were available for inclusion in the analysis. The mean number of milk yield, BCS, and BW records per lactation were 37, 23, and 23, respectively.

Data Editing and Generation of Variables of Interest

Milk Production. Only lactations that had at least 20 test-day records, with the first test-day record within 14 d postcalving and at least one test-day record after 180 d of lactation, were retained. A total of 2,463 lactations remained. Fat-corrected milk was calculated for each test day as per equations in NRC (2001).

Preliminary graphical analysis of the mean milk yield lactation curve and individual cow lactation curve revealed a profile similar to that described by the Wilmink exponential function (Wilmink, 1987) and recently presented by Roche et al. (2006) for grazing dairy cows. Although a similar-shaped profile was observed for fat, protein, and lactose yield, it was not as consistent across individual lactations. Therefore, the Wilmink exponential function was fitted to only milk and 4% FCM test-day yields within lactation and is described as:

$$Y_t = a + be^{-0.05t} + ct.$$

In this equation, Y_t = yield (kg) at day t of lactation, whereas a , b , and c = estimated parameters relating to the height of the curve, the initial phase of postcalving incline to peak, and the subsequent postpeak decline phase, respectively. The regression parameters were estimated for each cow lactation separately using PROC NLIN (SAS, 2006). The first derivative of the Wilmink function with respect to time (dY/dt) for each cow lactation was set equal to zero and solved for DIM to determine DIM at peak yield; DIM was rounded to the nearest whole integer. Peak yield was the yield corresponding to DIM at peak. Total milk and 4% FCM yield in the first 270 d were also derived as the definite integral of the function for each lactation. Correlations (PROC CORR; SAS, 2006) between peak yield and 270-d yield estimated using the Wilmink function and those derived from the raw test-day data as the maximum milk yield and the mean of the test-day yields multiplied by 270 were strong ($r > 0.96$), and thus only those derived from the Wilmink function are reported for milk and 4% FCM yield.

Average fat, protein, and lactose percentages were calculated as the average of all test-day records in the first 270 d of lactation. Cumulative milk and 4% FCM were also calculated within first 60 d of lactation as the average of test-day yields within that period multiplied by 60. Records were only retained if at least 5 test-day records were available within the first 60 d for each variable. Average fat, protein, and lactose percentages were also calculated within the first 60 d of lactation using the same criteria.

BCS and BW. The definition and generation of BCS and BW variables were previously outlined by Roche et al. (2007) and Berry et al. (2007) with the exception that BCS and BW at 305 d of lactation were replaced with BCS and BW at 270 d of lactation to correspond with the milk production variables generated. Two additional variables, lactation average BCS and average BW, were derived as the arithmetic means of all BCS and BW in the first 270 d of lactation. Other variables

of interest were BCS and BW at 8 wk before calving (precalving BCS), at calving, and at nadir. Amount of BCS and BW change between adjacent periods and the DIM to both BCS and BW nadir were also calculated.

Body condition score and BW precalving were determined as the BCS or BW record nearest to 8 wk precalving but always from 6 to 10 wk precalving. When 2 BCS or BW records were available equidistant from wk 8, the earlier record precalving was retained. Additionally, all BCS and BW records in the 9 wk before calving were retained to determine respective precalving change. A linear regression in PROC REG (SAS, 2006) was fitted through these records for each lactation separately and the linear coefficient determined; the linear regression was only fitted through lactations with at least 2 precalving records. The regression coefficient was recoded as 1, 2, or 3 if the regression coefficient was negative, zero, or positive, respectively.

The BCS and BW record considered to be that at calving was the first record postcalving but within 7 d of calving. Nadir BCS was the first postcalving record immediately followed by 2 greater consecutive values; nadir BW was determined using the same methodology. The days postcalving corresponding to nadir BCS, or nadir BW were also retained.

The levels of BCS or BW change from 8 wk precalving to calving and from calving to nadir were calculated as the earlier BCS or BW record minus the later record; hence, a positive value is indicative of a loss in BCS or BW and vice versa.

Other Possible Explanatory Variables. Parity was recoded as 1, 2, 3, 4, and 5+. Week of the year at calving was determined for all lactations. Due to small numbers, cows calving before wk 27 (i.e., early July) were grouped together as were cows calving later than wk 35 (i.e., early September). Year of calving was categorized as year. The number of days dry was estimated for each multiparous cow as the number of days from the last milk test-day record in the previous lactation to the subsequent calving date of the cow. Because no records for days dry were available for primiparous cows nor for cows that were purchased, days dry were recoded into a class variable with 4 levels in which primiparous animals or animals with no previous lactation information were included in the first class, and the remaining 3 classes were from 39 to 79 d dry, 80 to 119 d dry, or greater than 119 d dry. Parity, breed, week of year at calving, year of calving, and treatment farmlet operated on the research farm since 1986 were considered as class variables. These variables are the same as those described by Roche et al. (2007) and Berry et al. (2007) using the same data set to that used in the present study, when they related BCS and BW to fertility and udder health, respectively.

Statistical Analyses

All data were analyzed using mixed models in PROC MIXED (SAS, 2006). Cow was included as a random effect. Based on minimization of the Akaike information criterion, an unstructured correlation structure was assumed among records within cow. Significance of an independent variable in the model was based on the *F*-test. Preliminary analyses of all the milk production variables revealed that parity, year, breed, week of calving, and treatment farmlet significantly ($P < 0.05$) affected most of the milk production variables. Therefore, those independent variables were always included in the mixed model. A series of analyses were undertaken whereby only 1 BCS or BW variable was included in the model simultaneous with the aforementioned confounding variables; all BCS and BW variables were treated as continuous. Higher-order polynomials of the BCS and BW variables were also tested in the model. Significant interactions between each of the BCS and BW variables and either parity or breed were also investigated.

RESULTS

Mean ($\pm$ SD) BCS precalving, at calving, and at nadir were 4.69 (0.62), 4.72 (0.64), and 3.80 (0.61), respectively, on the 1 to 10 BCS scale. This is approximately equivalent to 2.84, 2.85, and 2.52 BCS units, respectively, on the 5-point scale (Roche et al., 2004). Mean ($\pm$ SD) BW precalving, at calving, and at nadir were 468 (71), 447 (76), and 390 (66) kg, respectively. Days in milk to nadir BCS and BW averaged 48 and 27 d, respectively. A complete list of the BCS variables was presented by Roche et al. (2007).

Milk Yield

The median R^2 values obtained from fitting the Wilink function to the milk and 4% FCM yield data were 0.84 and 0.76, respectively, indicating a good fit to the data. The mean ($\pm$ SD) values for the *a*, *b*, and *c* parameters of the Wilink function when fitted to milk yield were 24.4 (5.55), -7.4 (5.20), and -0.063 (0.022), respectively; the corresponding values when fitted to 4% FCM yield were 25.5 (5.32), -5.83 (5.81), and -0.0586 (0.0233), respectively. Mean ($\pm$ SD) 60-d and 270-d milk yields were 1,213 (287) kg and 4,141 (874) kg, respectively. Corresponding yields for 4% FCM were 1,310 (288) kg and 4,766 (818) kg, respectively.

The quantified effect of BCS and BW on the *a*, *b*, and *c* parameters of the Wilink functions for milk and 4% FCM yield as well as peak milk yield and

DIM to peak yield are summarized in Tables 1 and 2, respectively. Table 3 presents the effect of BCS and BW on cumulative 60-d and 270-d milk and 4% FCM yield. Body condition score 8-wk precalving was positively associated with the height of the lactation profile (the *a* parameter) and the slope of the postcalving incline (the *b* parameter), depicting a steeper incline to peak with increasing precalving BCS. The negative association between precalving BCS and rate of postpeak decline (the *c* parameter) in both milk and 4% FCM yield reflects a less persistent lactation in cows that were fatter 8 wk precalving. Despite this, precalving BCS had a positive effect on peak, 60-d and 270-d milk, and 4% FCM yield. For each unit increase in BCS 8-wk precalving, 60-d milk and 4% FCM yield increased linearly by 32.5 and 55.8 kg/cow, respectively, and 270-d milk and 4% FCM yield increased 89.2 and 114.0 kg/cow, respectively.

Precalving BCS change did not affect the shape of the lactation curve, nor did it affect 60-d or 270-d milk or 4% FCM yield. It did, however, affect DIM to peak milk yield, with cows that lost condition precalving having a shorter interval (2.8 d/BCS unit; SE = 0.84) to peak. Similar trends to those recorded for BCS were evident in the effect of precalving BW on the milk production variables, although this was sometimes breed dependent, with precalving BW having a greater positive effect in Holstein-Friesian cows than in Jerseys.

Body condition score at calving and nadir were nonlinearly associated with the height of the lactation curve (parameter *a*) and the postpeak decline (parameter *c*) but did not affect the exponential rate of acceleration to peak milk. The lactation profiles for milk and 4% FCM yield of cows calving at different BCS are illustrated in Figures 1 and 2, respectively. Peak milk and 4% FCM yield, DIM to peak milk and 4% FCM yield, and 60-d and 270-d milk and 4% FCM yield were also nonlinearly associated with BCS at calving.

The highest lactation curve, greatest peak, least persistency and greatest 60-d and 270-d milk and 4% FCM yield were obtained from cows calving at a BCS of 6.0 to 6.5 units or cows with a nadir BCS of 4.0 to 4.5 units. However, the effect of calving and nadir BCS diminished with increasing condition (Figure 3). For example, increasing calving BCS from 2.5 to 5.0 (equivalent of 2.0 to 3.0 in a 5-point BCS system; Roche et al., 2004) resulted in an increase of 482 and 624 kg in 270-d milk and 4% FCM yield, respectively. In comparison, increasing BCS from 5.0 to 7.5 (equivalent of 3.0 to 4.0 in a 5-point BCS system; Roche et al., 2004) only resulted in an additional 71 and 66 kg of milk and 4% FCM, respectively, and the majority of this (78 and 93

Table 1. Partial regression coefficients¹ of the parameters of the Wilmink function fitted to test-day milk and 4% FCM yield, peak milk and 4% FCM yield, and DIM to peak milk and 4% FCM yield on precalving, calving and nadir BCS, BCS change to nadir, and DIM to nadir BCS

Item	<i>a</i>	<i>b</i>	<i>c</i> × 10 ⁻³	Peak yield (kg)	DIM to peak (d)
Milk					
Precalving	0.51 (0.181)	0.51 (0.254)	-1.97 (0.875)	0.59 (0.152)	-2.6 (0.66)
At calving ²	3.90 × BCS - 0.31 × BCS² (0.947) (0.0974)	-0.26 (0.177)	-15.01 × BCS + 1.21 × BCS² (4.749) (0.489)	4.22 × BCS - 0.35 × BCS² (0.788) (0.081)	-9.2 × BCS + 0.85 × BCS² (3.89) (0.400)
At nadir ²	4.13 × BCS - 0.46 × BCS² (0.794) (0.102)	0.25 (0.183)	-15.43 × BCS + 1.83 × BCS² (3.929) (0.508)	3.96 × BCS - 0.45 × BCS² (0.661) (0.085)	-9.4 × BCS + 1.10 × BCS² (3.20) (0.415)
Change to nadir ^{2,3}	0.36 (0.114)	-0.43 (0.180)	-1.81 (0.57)	1.01 0.06 0.22 0.19 0.18 (0.209) (0.220) (0.209) (0.208) (0.150)	-2.4 × BCS + 1.13 × BCS² (1.19) (0.522)
DIM to nadir	0.008 (0.0011)	-0.0002 (0.0017)	-0.04 (0.0057)	0.007 (0.0009)	-0.01 (0.0047)
4% FCM					
Precalving	0.70 (0.177)	0.97 (0.279)	-3.67 (0.920)	1.08 (0.178)	-4.0 (0.760)
At calving ²	4.31 × BCS - 0.32 × BCS² (0.973) (0.100)	0.17 (0.197)	-16.43 × BCS + 1.20 × BCS² (0.512) (0.527)	5.03 × BCS - 0.39 × BCS² (0.939) (0.097)	-11.6 × BCS + 0.95 × BCS² (4.67) (0.481)
At nadir ²	3.75 × BCS - 0.35 × BCS² (0.807) (0.104)	0.04 (0.203)	-13.93 × BCS + 1.31 × BCS² (4.203) (0.544)	4.03 × BCS - 0.41 × BCS² (0.783) (0.101)	-10.3 × BCS + 1.21 × BCS² (3.84) (0.498)
Change to nadir ²	0.25 (0.118)	0.14 (0.189)	-1.04 (0.616)	1.17 × BCS - 0.379 × BCS² (0.288) (0.126)	3.88 × BCS + 1.228 × BCS² (1.417) (0.6225)
DIM to nadir ²	0.008 (0.0012)	0.0024 (0.0019)	-0.04 (0.0062)	0.0082 (0.0011)	-0.049 × DIM - 0.00013 × DIM² (0.0163) (0.000064)

¹Solutions of factors that are significantly ($P < 0.05$) associated with the dependent variable are in bold (SE underneath in parentheses).²Quadratic regression term was significant, and thus linear and quadratic solutions are reported.³A significant 2-way interaction with parity existed, so solutions presented are, from left to right, representative of parity 1, 2, 3, 4, and 5+, respectively.

Table 2. Partial regression coefficients¹ of the parameters of the Wilmink function fitted to test-day milk and 4% FCM yield, peak milk and 4% FCM yield, and DIM to peak milk and 4% FCM yield on precalving, calving and nadir BW, BW change to nadir, and DIM to nadir BW

Item	$a \times 10^{-2}$					$b \times 10^{-3}$		$c \times 10^{-5}$					Peak yield (kg $\times 10^{-2}$)					DIM to peak (d $\times 10^{-2}$)	
Milk																			
Precalving ²	2.6	1.2				-0.2		-7.0				2.3				-3.3			
	(0.27)	(0.69)				(3.67)		(0.13)				(0.22)				(0.94)			
At calving ²	2.1	0.5				-5.3		-7.0	-2.0			2.0	0.6			-1.7			
	(0.15)	(0.40)				(2.14)		(0.72)	(1.91)			(0.12)	(0.33)			(0.58)			
At nadir ²	3.1	1.0				2.5		-8.0	-2.1			2.9	1.1			-3.1			
	(0.21)	(0.50)				(2.75)		(0.94)	(1.90)			(0.16)	(0.41)			(0.74)			
Change to nadir ³	0.6					17.7 $\times$ BW - 0.24 $\times$ BW²		-3.1				2.65 $\times$ BW - 0.01 $\times$ BW²				-7.39 $\times$ BCS + 0.060 $\times$ BCS²			
	(0.20)					(8.45)	(0.061)	(0.99)				(0.469)	(0.003)			(2.33)	(0.0168)		
DIM to nadir ^{3,4}	3.8	2.4	-0.4	1.9	0.9	523 $\times$ DIM - 3.0 $\times$ DIM²		-15.0	-8.0	6.0	-4.2	-3.1	4.19 $\times$ DIM - 0.017 $\times$ DIM²		-22.5 $\times$ DIM + 0.13 $\times$ DIM²				
	(0.75)	(0.82)	(0.87)	(0.86)	(0.62)	(13.2)	(0.14)	(3.7)	(4.2)	(4.4)	(4.4)	(3.2)	(0.72)	(0.0074)	(3.58)	(0.367)			
4% FCM																			
Precalving ⁴	2.4					12.5		-8.0				3.0				-6.0			
	(0.25)					(3.99)		(1.30)				(0.25)				(1.08)			
At calving ^{2,3,4}	2.3	1.4				4.0		-8.0				2.2	2.8	2.8	2.9	2.2	-14.8 $\times$ BW + 0.01 $\times$ BW²		
	(0.15)	(0.39)				(2.37)		(0.75)				(0.26)	(0.25)	(0.25)	(0.25)	(0.19)	(4.37)	(0.005)	
At nadir ³	7.1 $\times$ BW - 0.004 $\times$ BW²					3.6		-25.0 $\times$ BW + 0.018 $\times$ BW²			6.0 $\times$ BW - 0.003 $\times$ BW²			-4.3					
	(1.10)	(0.0013)				(3.03)		(5.80)	(0.0001)			(1.06)	(0.0013)		(0.89)				
Change to nadir ³	4.5					33.6 $\times$ BW - 0.23 $\times$ BW²		-2.0				3.1 $\times$ BW - 0.017 $\times$ BW²			-13.0 $\times$ BW + 0.789 $\times$ BW²				
	(2.05)					(9.55)	(0.069)	(1.1)				(0.57)	(0.0041)		(2.78)		(0.020)		
DIM to nadir ³	2.15					64.0 $\times$ DIM - 0.38 $\times$ DIM²		-7.0				5.69 $\times$ DIM - 0.023 $\times$ DIM²			-21.4 $\times$ DIM - 0.11 $\times$ DIM²				
	(0.385)					(14.77)	(0.151)	(2.01)				(0.866)	(0.0089)		(4.3)		(0.044)		

¹Solutions of factors that are significantly ($P < 0.05$) associated with the dependent variable are in bold (SE underneath in parentheses).

²A significant interaction between BW and breed existed. The first and second solutions refer to the Holstein-Friesian and Jersey breed, respectively.

³Quadratic regression term was significant, and thus linear and quadratic solutions are reported

⁴A significant 2-way interaction with parity existed, so solutions presented are, from left to right, representative of parity 1, 2, 3, 4, and 5+, respectively

Table 3. Partial regression coefficients¹ of cumulative 60-d and 270-d milk and 4% FCM yield on BCS and BW precalving, at calving, and at nadir, as well as change from calving to nadir and DIM to nadir

Item	BCS (BCS units)				BW (kg)			
	60-d yield (kg)		270-d yield (kg)		60-d yield (kg)		270-d yield (kg)	
Milk								
Precalving ²	32.5 (8.89)		89.2 (24.79)		1.3 (0.13)	0.7 (0.34)	3.9 (0.39)	1.0 (1.00)
At calving ^{2,3}	235.4 × BCS – 19.5 × BCS ² (47.10) (4.84)		439.7 × BCS – 32.9 × BCS ² (128.96) (13.24)		1.1 (0.08)	0.4 (0.20)	3.0 (0.22)	0.8 (0.57)
At nadir ^{2,3}	258.1 × BCS – 28.5 × BCS ² (39.28) (5.06)		515.0 × BCS – 53.8 × BCS ² (108.20) (13.87)		258.1 × BW – 28.5 × BW ² (39.28) (5.06)		5.0 (0.30)	2.4 (0.71)
Change to nadir ^{3,4}	59.62 – 0.04 × BCS + 0.32 × BCS ² – 5.71 × DIM + 1.77 × DIM ² (12.43) (13.14) (12.49) (12.41) (8.93)		147.7 × BCS – 53.22 × BCS ² (38.64) (16.900)		1.05 × BCS – 0.0075 × BCS ² (0.28) (0.00202)		2.7 × BCS – 0.016 × BCS ² (0.76) (0.0055)	
DIM to nadir	0.46 (0.056)		0.80 (0.152)		1.43 (0.182)		3.63 (0.49)	
4% FCM								
Precalving ²	55.8 (9.20)		114.0 (24.48)		1.5 (0.13)		3.8 (0.38)	1.4 (0.96)
At calving ^{2,3}	286 × BCS – 22.1 × BCS ² (50.2) (5.17)		585 × BCS – 44.7 × BCS ² (132.7) (13.64)		1.4 (0.08)	1.0 (0.20)	3.2 (0.21)	1.9 (0.56)
At nadir ^{2,3}	258 × BCS – 25.1 × BCS ² (41.8) (5.39)		588 × BCS – 48.8 × BCS ² (111.3) (14.32)		2.2 (0.10)	1.6 (0.25)	5.1 (0.28)	3.4 (0.69)
Change to nadir ³	47.95 × BCS – 16.84 × BCS ² (15.478) (6.787)		143.2 × BCS – 44.92 × BCS ² (40.21) (17.607)		1.4 × BW – 0.0087 × BW ² (0.30) (0.0022)		3.4 × BCS – 0.022 × BCS ² (0.79) (0.0057)	
DIM to nadir ³	0.52 (0.061)		1.09 (0.158)		27.9 × DIM + 0.0085 × DIM ² (7.64) (0.0027)		3.95 (0.513)	

¹Solutions of factors that are significantly ($P < 0.05$) associated with the dependent variable are in bold (SE underneath in parentheses).²A significant interaction between BW and breed existed. The first and second solutions refer to the Holstein-Friesian and Jersey breed, respectively.³Quadratic regression term was significant, and thus linear and quadratic solutions are reported.⁴A significant 2-way interaction with parity existed, so solutions presented are, from left to right, representative of parity 1, 2, 3, 4, and 5+, respectively.

Figure 1. Mean milk lactation profiles for cows calving at BCS ≤ 3.5 units ($\blacklozenge$), 4.0 ($\blacksquare$), 4.5 ($\blacktriangle$), 5.0 ($\times$), 5.5 ($*$), and ≥ 6.0 units ($\bullet$) on the 10-point BCS scale.

kg, respectively) was achieved by increasing calving BCS from 5.0 to 6.0.

A general tendency for the relationship between BW at calving and nadir and the various attributes of the milk lactation profiles (Table 2) to be dependent on

breed was discovered, with the height of the milk and 4% FCM profile greater, the degree of milk yield persistency less, and peak milk yield greater in Holstein-Friesians compared with Jersey cows. Irrespective of breed, heavier animals had shorter intervals from

Figure 2. Mean 4% FCM (kg/d) lactation profiles for cows calving at BCS ≤ 3.5 units ($\blacklozenge$), 4.0 ($\blacksquare$), 4.5 ($\blacktriangle$), 5.0 ($\times$), 5.5 ($*$), and ≥ 6.0 units ($\bullet$) on the 10-point BCS scale.

Figure 3. Nonlinear effect of BCS at calving on 60-d milk (■) and 4% FCM (□) yield, 270-d milk (▲) and 4% FCM (△) yield, and peak milk (◆) and 4% FCM yield (◇).

calving to peak milk yield. A significant interaction between parity and DIM to nadir BW existed for the *a* and *c* parameter, with DIM to nadir BCS exhibiting greater influence on the height of the lactation curve and lactation persistency in first-parity cows than older herd mates. Body weight change precalving did not significantly affect any of the variables associated with the milk lactation profile.

Greater BCS loss to nadir was associated with an increase in the height of the lactation curves as well as greater peak milk and 4% FCM yield. However, there was an interaction between BCS change postpartum and parity on peak milk yield, with the positive association with BCS loss only significantly different from zero in first-parity animals. No such interaction was evident in 4% FCM yield. Whole lactation milk and 4% FCM yield were also positively associated with BCS loss between calving and nadir, with yield increasing at a declining rate with increasing BCS loss in early lactation. Cows that lost 1 BCS unit from calving to nadir were expected to yield 94.5 kg more milk across the 270-d lactation compared with animals that did not lose any body condition. Similarly, cumulative 60-d and 270-d milk yield was positively associated with greater BW loss to nadir. Cumulative 60-d and 270-d milk yield were greater with longer DIM to BCS and BW nadir.

Milk Composition

Mean ($\pm$ SD) 270-d fat, protein, and lactose concentrations were 4.93% (0.69), 3.60% (0.29), and 4.84% (0.20), respectively. Average 60-d and 270-d milk fat percentage increased linearly with increasing BCS and BW precalving, at calving, and at nadir (Table 4). The effect of BCS precalving on milk fat percentage was greater in younger cows, whereas the effect of BW at calving and nadir was greater in Jersey cows compared with Holstein-Friesian cows. A 1-unit increase in calving BCS was associated with a 0.1 percentage unit increase in 60-d fat content.

Change in BCS or BW precalving did not significantly affect milk fat content. In comparison, although BCS or BW loss from calving to nadir did not significantly affect average fat percentage in the first 60 d of lactation, increased BCS loss to nadir was associated with a reduced fat percentage averaged over the whole 270-d lactation. Milk fat content in the first 60 d of lactation was not significantly affected by DIM to BCS nadir, although it increased with DIM to BW nadir.

Neither BCS precalving nor at calving significantly affected milk protein content averaged across the first 60 or 270 d of lactation (Table 5), although protein percentage increased linearly with increasing BCS at nadir. Protein percentage was negatively associated with postcalving BCS loss, the effect being particularly

Table 4. Partial regression coefficients¹ of average 60-d and 270-d milk fat content on BCS and BW precalving, at calving, and at nadir, as well as change from calving to nadir and DIM to nadir

Milk fat	BCS (BCS units)				BW (kg)			
	60-d ($\% \times 10^{-2}$)		270-d ($\% \times 10^{-2}$)		60-d ($\% \times 10^{-4}$)		270-d ($\% \times 10^{-4}$)	
Precalving ²	20.9 (3.42)	16.2 (3.03)	9.5 (2.92)	8.8 (2.38)	3.0 (1.24)	13.7 (2.97)	–2.1 (2.29)	
At calving ³		10.4 (1.16)			2.3 (0.82)	14.0 (1.59)	22.9 (4.15)	1.6 (1.15)
At nadir ³		13.4 (1.31)			7.1 (0.95)	17.6 (2.32)	27.9 (5.45)	7.6 (1.76)
Change to nadir		–0.5 (1.1)			–2.5 (0.08)	8.1 (1.85)	–2.3 (1.28)	
DIM to nadir		0.016 (0.011)			–0.006 (0.007)	8.3 (3.49)	–2.3 (2.38)	

¹Solutions of factors that are significantly ($P < 0.05$) associated with the dependent variable are in bold (SE underneath in parentheses).

²A significant 2-way interaction with parity existed, so solutions presented are, from left to right, representative of parity 2, 3, 4, and 5+, respectively.

³A significant interaction between BW and breed existed. The first and second solutions refer to the Holstein-Friesian and Jersey breed, respectively.

pronounced in primiparous cows. Average 60-d protein percentage was almost 0.1 percentage units lower in cows that lost 1 BCS unit from calving to nadir compared with those that did not lose any body condition.

Precalving BW was nonlinearly associated with protein percentage, increasing at a declining rate up to a BW of 500 kg and declining thereafter. Cows that lost or held BW constant in the 8 wk precalving had a 2.5 (SE = 10.62) and 7.2 (SE = 4.10) percentage units $\times 10^{-2}$ lower protein percentage, respectively, compared with animals that gained BW precalving. The effect of calving BW on milk protein percentage was breed-dependent, with average protein content of milk from Jersey cows declining with increasing calving BW but

increasing in Holstein-Friesian cows. Consistent with the effect of BCS, protein percentage was reduced in cows that lost more BW to nadir and that had a delayed interval to nadir BW (a longer negative energy balance).

Lactose percentage, averaged across the first 60 d of lactation, increased by more than 0.01 and 0.02 percentage units per unit increase in BCS at calving and nadir, respectively (Table 6). Precalving BCS change did not significantly affect lactose percentage, but lactose percentage decreased linearly as the amount of BCS lost from calving to nadir increased. Lactose percentage in early lactation increased with BW at calving and BW at nadir but tended to plateau

Table 5. Partial regression coefficients¹ of average 60-d and 270-d milk protein content on BCS and BW precalving, at calving, and at nadir, as well as change from calving to nadir and DIM to nadir.

Milk protein	BCS (BCS units)						BW (kg)	
	60-d ($\% \times 10^{-3}$)			270-d ($\% \times 10^{-3}$)			60-d ($\% \times 10^{-4}$)	270-d ($\% \times 10^{-4}$)
Precalving ²	3.7 (8.60)			–6.4 (6.58)			–0.6 (1.40)	20.3 $\times$ BW – 0.02 $\times$ BW² (7.70) (0.0001)
At calving ³	10.0 (6.01)			–4.0 (4.55)			1.2 (0.80)	–1.8 6.67 (0.63) (1.64)
At nadir ³	99.4 (6.36)			54.1 (5.09)			17.2 31.3 (1.08) (2.55)	6.49 22.78 (0.92) (2.11)
Change to nadir ^{2,4}	–91.1 $\times$ BCS + 14.1 $\times$ BCS² (13.62) (5.95)	–69.4	–27.8	–32.9 –28.4 –38.1 (9.54) (9.23) (8.77) (8.65) (6.31)			–10.8 (0.92)	–10.0 $\times$ BCS + 2.0 $\times$ BCS² (0.0322) (0.014)
DIM to nadir ²	–0.61 $\times$ DIM + 0.0019 $\times$ DIM² (0.161) (0.0005)			–0.45 $\times$ DIM + 0.0012 $\times$ DIM² (0.12) (0.0005)			–4.3 (1.79)	–5.9 (1.32)

¹Solutions of factors that are significantly ($P < 0.05$) associated with the dependent variable are in bold (SE underneath in parentheses).

²Quadratic regression term was significant, and thus linear and quadratic solutions are reported.

³A significant interaction between BW and breed existed. The first and second solutions refer to the Holstein-Friesian and Jersey breed, respectively.

⁴A significant 2-way interaction with parity existed, so solutions presented are, from left to right, representative of parity 1, 2, 3, 4, and 5+, respectively.

Table 6. Partial regression coefficients¹ of average 60-d and 270-d milk lactose content on BCS and BW precalving, at calving, and at nadir, as well as change from calving to nadir and DIM to nadir

Milk lactose	BCS		BW	
	60-d ($\% \times 10^{-3}$)	270-d ($\% \times 10^{-3}$)	60-d ($\% \times 10^{-4}$)	270-d ($\% \times 10^{-4}$)
Precalving	6.4 (5.68)	0.5 (4.46)	-0.8 (0.97)	-2.3 (0.80)
At calving ²	13.1 (3.74)	1.5 (2.80)	$7.6 \times \text{BW} - 0.006 \times \text{BW}^2$ (2.96) (0.0001)	-0.02 (0.39)
At nadir ²	29.9 (4.24)	15.6 (3.23)	$16.7 \times \text{BW} - 0.012 \times \text{BW}^2$ (3.84) (0.0001)	2.8 (0.59)
Change to nadir	-8.1 (3.49)	-8.8 (2.60)	-1.6 (0.58)	-1.5 (0.43)
DIM to nadir	0.08 (0.003)	-0.002 (0.025)	3.8 (1.10)	-0.3 (0.81)

¹Solutions of factors that are significantly ($P < 0.05$) associated with the dependent variable are in bold (SE underneath in parentheses).

²Quadratic regression term was significant, and thus linear and quadratic solutions are reported.

at higher BW. Greater BW loss postcalving was associated with lower lactose percentage. Animals that lost BW in the 8 wk precalving had a lower milk lactose content of 0.014 percentage units (SE = 0.0068) compared with animals that were gaining BW precalving.

DISCUSSION

The importance of BCS has been reputed for decades (Grainger and McGowan, 1982; Wildman et al., 1982; Waltner et al., 1993; Domecq et al., 1997a), but reported responses have been variable (see reviews by Broster and Broster, 1998; Stockdale, 2001). Much of the published data relating BCS to milk production have been from studies using small numbers of cows, in which only 2 or 3 levels of BCS were investigated or from studies in which cows were fed TMR. Stockdale (2001) referred to this lack of available information on the effect of BCS on milk yield for pasture-based dairy cows. Furthermore, although BCS has been extensively investigated, little is known about the effects of BW and BW change on milk production.

Presented data support a nonlinear effect of calving BCS on peak, 60-d and 270-d milk, and 4% FCM yield, consistent with positive effect of BCS on milk yield reported by Bouchier et al. (1987), Waltner et al. (1993), and Stockdale (2004a,b, 2005), and this nonlinearity extends to the shape of the milk production curve. Optimum calving BCS for milk and 4% FCM yield was approximately 6.5 BCS units, with the marginal response in milk yield to greater calving BCS negative beyond this. However, there was very little increase in milk production beyond a BCS of 5.0 to 5.5 (270-d milk yield increased by 209 and 144 kg for a calving BCS increase of 3.0 to 4.0 and 4.0 to 5.0, respectively, but only by 45 kg from a BCS of 5.5 to 6.5). The curvilinear nature of the milk yield response to calving

BCS may be one reason for inconsistent results in previous studies. Comparisons generally involved only 2 or 3 BCS strata, making it difficult to define an optimum BCS or determine a change in the slope of the milk response to increasing BCS. In addition, the majority of BCS treatments imposed in previous studies were in excess of 2.5 units in the 5-point scale (Broster and Broster, 1998). Data presented here and by Waltner et al. (1993) indicate that the marginal milk production response to increasing BCS above 2.5 units would be small, and comparisons in this range are less likely to reveal significant milk production responses.

The milk yield response to calving BCS reported here is similar to those reported by Waltner et al. (1993) and Domecq et al. (1997a) in TMR-fed cows. Domecq et al. (1997a) reported a 545.5-kg increase in milk yield with incremental increases in BCS between dry-off and calving (i.e., increasing BCS from 2.5 to 5.0 in the 10-point scale; Roche et al., 2004), similar to the 482-kg increase in milk yield (624 kg 4% FCM) recorded in the current study with increasing calving BCS. The data presented by Bouchier et al. (1987), in which the positive effect of calving BCS on peak milk declined with increasing BCS, are also consistent with the data presented here. Bouchier et al. (1987) found a 5 kg/d increase in milk yield when calving BCS increased from 1.25 to 2.25 (5-point scale). But this response declined to only 1 kg/d for a further increase of 1.5 BCS units at calving. A similar trend in the peak milk response to calving BCS was evident in the current data set (5.6 and 2.9 kg/d, respectively). Both of these studies are also consistent with the results presented by Stockdale (2004a,b, 2005), who also reported a 1.0 to 1.1 kg/d milk yield response/unit change in calving BCS from 4 to 6 (8-point scale). Results from the current study also point to a 1.0 kg of

milk/d per BCS unit when calving BCS increased in the bottom half of the range described by Stockdale (2004a,b, 2005).

Despite some inconsistencies in the reported literature, the similarity in the response to either calving BCS or BCS change across various studies is remarkable, especially considering the large differences in systems (intensive grazing vs. confinement), diets (pasture vs. TMR), and mean milk production/cow (4,141 and 9,541 kg of milk in the current study and that presented by Waltner et al., 1993, respectively) represented. The consistency in the reported results raises 2 important points.

1. The calving BCS associated with the greatest milk production is 6.5 in the 10-point system of body condition scoring (approximately 3.5 in the 5-point system; Roche et al., 2004). However, there appears to be little increase in milk production by increasing calving BCS beyond 5.0 (equivalent of 3.0 in the 5-point system; Roche et al., 2004), irrespective of cow milk yield or whether cows are being fed TMR in confinement vs. being intensively grazed on pasture (Waltner et al., 1993).
2. Experimental studies investigating the relationship between calving BCS and an applied treatment (e.g., postcalving concentrate supplementation) need to account for the nonlinear nature of the milk yield response to calving BCS and include at least 3, and preferably 4, calving BCS treatments with sufficient divergence to account for the quadratic response.

Many experiments in the United Kingdom investigating the interaction between calving BCS and early lactation nutrition have indicated a lack of effect of calving BCS on milk production when cows are well fed in early lactation (Garnsworthy and Topps, 1982a,b; Garnsworthy and Jones, 1987, 1993; Broster and Broster, 1998). This is not supported by the results reported here or those provided by Waltner et al. (1993) and Domecq et al. (1997a), the cows in the latter two studies being fed a balanced TMR. However, it is possible that the BCS treatments tested in the studies referred to by Broster and Broster (1998) were not sufficiently divergent or that the low-BCS treatment was not sufficiently low to have a substantial effect on milk production. We contend that this is also the reason for the lack of effect of calving BCS on milk production reported by Ruegg and Milton (1995), in which 82% of cows had a calving BCS >3.0 (5-point scale). A recently reported interaction between calving BCS and level of nutrition in early lactation (Stockdale, 2004a) also supports this premise. Stockdale (2004a) reported a

positive response to calving BCS in grazing dairy cows supplemented with 6 kg of concentrates but only up to a BCS of 5 (8-point scale). Increasing calving BCS to 6 did not increase milk yield unless cows were at least partially underfed.

The positive effect of calving BW on milk production is consistent with the positive effect reported by Sieber et al. (1988) and Macdonald et al. (2005). However, it is not in agreement with the results of Markusfeld and Ezra (1993), who reported a positive effect of wither height but a negative effect of BW in first lactation heifers. These results indicate a positive effect of cow size but a negative effect when this is positively associated with BW, possibly indicating one of two things:

1. to achieve the greater BW, the heifers in the study reported by Markusfeld and Ezra (1993) experienced a period of accelerated growth before puberty, resulting in reduced mammary parenchymal development (Meyer et al., 2006) and subsequent milk production (Macdonald et al., 2005) or
2. the heifers were excessively fat, resulting in reduced milk production consistent with the data presented here and by Waltner et al. (1993) and Macdonald et al. (2005).

Another interesting result from the current study was the effect of BCS and BW at calving and nadir and BCS and BW change between calving and nadir on the general shape of the lactation profile. Both calving and nadir parameters were positively associated with the height of the lactation curve (parameter a), explaining the positive effect of BCS and BW at these key times on peak, 60-d and 270-d milk, and 4% FCM yield. Calving or nadir BCS did not affect the rate of milk yield increase to peak, but the negative effect of BCS on the persistency of the milk production profile indicates a declining effect of calving and nadir BCS on milk production as lactation progresses. This is consistent with the earlier results of Land and Leaver (1981) and Treacher et al. (1986). It is also consistent with the timeline of BCS mobilization (DIM to nadir BCS was 48 d) and the cessation of nutrient supply from tissue stores being directed toward milk production.

However, the effect of calving BCS on 270-d milk yield was, on average, 140% greater than the effect on 60-d milk yield. This indicates a positive effect of calving BCS (up to BCS 6.5) on daily milk yield beyond nadir BCS. The reason for a positive effect of calving BCS on milk yield beyond the period of nutrient supply from body tissue is not known. However, it must be a result of either an increased mid and late lactation DMI in cows that calved in better condition, a reduc-

tion in the partitioning of nutrients to tissue store replenishment in these cows, or both. A positive effect of calving BCS on DMI is contrary to the majority of previous research indicating a negative effect of calving BCS and DMI (Broster and Broster, 1998; Stockdale, 2001). However, this negative effect of calving BCS on DMI was only measured in early lactation, with no reports of an effect of calving BCS on mid or late lactation cows available. It is possible that the greater milk yield from increased calving BCS is a result of increased mammary cell proliferation and that this results in an increase in DMI after the initial suppression (i.e., the mammary gland drives DMI). This is the accepted reason for the positive carryover effect of increased milking frequency in early lactation on milk yield (Hale et al., 2003) and for the increased DMI following bST administration, which follows rather than precedes the increase in milk yield (Bauman, 1999). Further research is required to determine the longer-term effect of calving BCS on DMI.

The second possible reason for a positive association between calving and nadir BCS and milk production is a reduced partitioning of nutrients to BCS gain in animals in greater calving and nadir BCS. Mitchel and Keesey (1977) reported an innate desire of mammals to maintain a physiological steady state with respect to BCS. If fatter than this ideal, neurological stimuli reduce DMI, and if thinner, animals will increase DMI and partition more nutrients to BCS gain. This theory is consistent with a reduced partitioning of nutrients to BCS gain (postnadir) in fatter cows and a consequently greater milk yield (assuming DMI is not suppressed). This theory would also explain the declining effect of calving (and nadir) BCS on milk yield as lactation progresses, with the difference in nutrients being partitioned to BCS gain declining as the difference in BCS becomes smaller. Further research is required to determine whether the postnadir effect of calving BCS on milk production is related to DMI, nutrient partitioning, or both.

The effect of BCS and BW on milk composition is consistent with the literature (Stockdale, 2004a,b, 2005). Fat content increased linearly with increasing BCS and BW at all measured time points (0.1 and 0.02% fat up to 60 and 270 DIM, respectively, per BCS unit at calving). This probably reflects the increased availability of NEFA from greater BCS mobilization, at least in early lactation when the difference is greatest. This greater mobilization and the resultant increase in glycerol availability for gluconeogenesis may also explain the positive association between BCS and milk lactose concentration. The effect of BCS and BW on milk protein concentration is less clear, although a greater BCS and BW at nadir or less BCS and BW

loss between calving and nadir was associated with greater milk protein concentration. Results indicate an interaction between parity and BCS precalving (% of fat) and the postcalving loss of BCS (% of protein). These data reflect a greater importance of periparturient BCS and BCS change in first parity cows but that later parity cows (two and greater) are not differentially affected by BCS or BCS change. Berry et al. (2007) also reported an interaction between parity and calving BCS on early lactation SCC. These findings suggest that heifers may benefit from a slightly greater BCS at calving (0.5 and 0.25 BCS units in the 10- and 5-point scales, respectively).

CONCLUSIONS

Body condition score at calving and nadir as well as loss of BCS between calving and nadir had significant effects on milk production, which was also reflected by BW and BW change. Results are consistent with data presented from studies involving cows fed TMR. The optimum calving BCS for milk production is approximately 6.5 in the 10-point scale for condition scoring and 3.5 in the 5-point scale. However, there is little increase in milk yield beyond a BCS of 5.0 and 3.0 in the 10- and 5-point scales, respectively.

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