Meta-Analysis to Assess Effect of Prepubertal Average Daily Gain of Holstein Heifers on First-Lactation Production*

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ABSTRACT

Decreased mammary development has been observed as prepubertal average daily gain (ADG) is increased; however, responses in first-lactation milk production to alterations in prepubertal ADG have been inconsistent across several experiments. Due to the continuous nature of ADG, body weight at calving (BWC), milk production, and milk composition, designing an experiment that encompasses a large range of ADG while maintaining an adequate number of animals at each ADG becomes prohibitive. Therefore, the objective of the current analysis was to quantitatively and statistically assess effects of alterations in prepubertal ADG and BWC on first-lactation production of milk, fat-corrected milk, milk fat, and milk protein. Eight studies that included Holstein heifers and were published within the past 15 yr were included in this analysis. The mixed model procedure of SAS was used to assess effects of prepubertal ADG and BWC on milk production independent of genetic or management differences that were evident between trials. Linear and quadratic effects of prepubertal ADG and BWC and their combinations were modeled including a random classification variable for each trial. Milk yield responses were associated quadratically with increasing prepubertal ADG; first-lactation production increased as prepubertal gains increased up to 799 g/d, the point of maximal milk production, whereas further increases in prepubertal ADG were associated with lower milk production. Increasing BWC within the range of 477 to 550 kg tended to linearly increase first-lactation milk production, but BWC significantly affected milk production in a model that included the linear and quadratic effects of ADG as well as linear BWC. In that model, which accounted for differences in calving weight, milk production was maximal at prepubertal ADG of 836 g/d. Milk protein yield was quadratically affected by alterations in prepu-

bertal ADG, and milk protein yield was maximized when prepubertal growth occurred at 836 g/d. This analysis also revealed that yield of milk fat remained relatively constant independent of alterations in prepubertal ADG, which occurred despite the significant quadratic effect on milk and milk protein yield.

(Key words: prepubertal growth, average daily gain, first-lactation production)

Abbreviation key: ADG = average daily gain, BWC = body weight after calving.

INTRODUCTION

Raising dairy heifers is a very important aspect of whole farm management that can be characterized as a long-duration, high-cost period that creates a lag in capturing a return on investment. Several management strategies have been proposed and tested to minimize costs associated with raising dairy heifers and to reduce the duration before first parturition (Heinrichs, 1993). Each of these strategies should have at their core the requirement that a cost reduction does not reduce the potential lifetime production of the dairy cow. Due to the nature of many management objectives and interactions among many of the variables involved, meeting all of these objectives simultaneously has not yet been achieved (Hoffman and Funk, 1992). Due to the dynamic nature of raising dairy replacements, the concept of optimality can be applied to improve the ability of dairy producers to make informed management decisions (Hoffman, 1997).

Growth rate of replacement heifers is one of the most frequently manipulated variables in experimental settings because of the potential impact on age at first calving, lifetime productivity, and feed costs (Heinrichs, 1993; Gabler et al., 2000). Growth in the prepubertal period is of particular interest, due to effects that growth rates have on mammary development (Sejrsen et al., 1982) and on early achievement of adequate size for breeding, which ultimately determines age at first calving; both of these factors can substantially affect whole farm profitability (Tozer and Heinrichs, 2001). Sinha and Tucker (1969) showed that allometric development of mammary tissue began at approximately 3

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mo of age and continued until the completion of several estrous cycles. Subsequent experiments have shown that mammary development (as assessed by quantities of mammary DNA) is negatively associated with high growth rates before puberty (Sejrsen et al., 1982; Capuco et al., 1995). There appears to be some variability in the literature, however, about the magnitude of the effect that prepubertal growth rate has on milk production. Several recent experiments have found that increasing average daily gain (ADG) before puberty decreases milk production in first lactation (Van Amburgh et al., 1998; Lammers et al., 1999; Radcliff et al., 2000), confirming early work on this subject (Swanson, 1960). Other experiments have failed to show significant associations between ADG and milk production in first lactation (Peri et al., 1993; Waldo et al., 1998; Abeni et al., 2000; Carson et al., 2000), and others have shown significant increases in milk production as prepubertal ADG increases (Stelwagen and Grieve, 1992). In reviewing literature, Foldager and Sejrsen (1987) and Sejrsen et al. (2000) suggested that prepubertal gains somewhere between 600 and 700 g/d result in subsequent maximum milk production for large-breed dairy cattle. They also reported that subsequent milk production was curvilinear as associated with the quadratic function of prepubertal ADG. If this is indeed the case, much of the discrepancy among experiments could be due solely to the choice of ADG in the experimental design and the number of treatments, assuming all other management practices between groups remained constant. The potential also exists that BW after calving (BWC) could affect conclusions made about prepubertal ADG if that factor is not controlled experimentally or adjusted statistically. Clark and Touchberry (1962) reported that first-lactation production of both milk and fat increased when BWC increased. Those results were more recently confirmed (Keown and Everett, 1986; Dobos et al., 2001); however, Sejrsen et al. (2000) questioned the validity of statistically adjusting first-lactation data by observed differences in BWC based on other experiments where milk production was unaffected.

Considering the continuous nature of ADG, BWC, milk production, and milk composition and to a potential nonlinear response, designing an experiment that encompasses a large range of ADG while maintaining an adequate number of animals at each ADG becomes prohibitive. Meta-analytic procedures allow for a quantitative, statistical treatment of many related, but independent, experiments while increasing the statistical power over any one experiment individually (Normand, 1999). Therefore, the objective of the current analysis was to quantitatively and statistically assess the effects that prepubertal ADG and BWC of Holstein heifers

have on milk production, FCM yield, milk fat, and milk protein in first lactation.

MATERIALS AND METHODS

Selection Criteria

Published studies that reported prepubertal heifer growth and subsequent first-lactation production were used for this analysis. Due to varied methodologies, management differences, genetic improvements, and breed differences, the following criteria were established to select treatments from within and across experiments. First, in an attempt to represent the most current information available, experiments were only considered eligible if published in the past 15 yr (since 1990). From those experiments, animals under study must have been Holstein or Holstein-Friesian crosses (1 experiment included in the final analysis reported Holstein-Friesian crosses and the remainder were Holsteins, but these differences were included in the analysis as a covariate). The objectives of experiments must have been to evaluate effects of ADG on first-lactation milk production, regardless of how ADG differences were achieved. Two experiments that altered ADG also had hormonal treatments (Lammers et al., 1999; Radcliff et al., 2000); those treatment group means were not included due to the possibility of biasing effects of ADG on milk production and insufficient replication across hormonal treatments. Experiments had to have altered ADG within the critical period (starting before 300 kg) for prepubertal mammary development (Foldager and Sejrsen, 1987), and experiments that altered ADG by using a stair-step or compensatory growth regimen were not included in the analysis due to inconsistent ADG during the critical mammary development period. Eight experiments met these criteria; totaling 21 treatment means and encompassing data from 472 cows (Stelwagen and Grieve, 1992; Peri et al., 1993; Van Amburgh et al., 1998; Waldo et al., 1998; Lammers et al., 1999; Abeni et al., 2000; Carson et al., 2000; Radcliff et al., 2000). Milk production responses to ADG from those experiments are shown graphically in Figure 1 and relevant descriptive statistics are summarized in Table 1.

Statistical Methodology

Many of the experiments presented their results in differing forms, such as milk production expressed as kilograms per day or for a fixed number of days. To enable comparison, all data were expressed as kilograms of milk produced per 305 d. Some experiments reported only milk fat and protein production yield and others reported percentages; those were converted to

Figure 1. Treatment means for milk production response to altering prepubertal average daily gain (ADG) for experiments included in the statistical analysis. Treatment means that were statistically different are connected by solid lines: $\square$ = Lammers et al., 1999; $\diamond$ = Radcliff et al., 2000; $\circ$ = Stelwagen and Grieve, 1992; $\triangle$ = Van Amburgh et al., 1998; those with dashed lines were not significantly different: $\times$ = Abeni et al., 2000; $\blacksquare$ = Carson et al., 2000; $\blacklozenge$ = Peri et al., 1993; $\blacktriangle$ = Waldo et al., 1998 (corn silage diet); and $\bullet$ = Waldo et al., 1998 (alfalfa silage diet).

the value that was not reported. Four percent FCM yield in experiments where it was not included and milk fat production and percentage for data presented by Van Amburgh et al. (1998) were calculated using treatment means according to the equation of Gaines (1928).

Following the previous calculations, data for milk production and FCM production were weighted according to their standard errors according to methodol-

ogy reported by St-Pierre (2001). Data associated with milk fat and milk protein were not weighted according to standard errors because of the presence of calculated values. It should also be noted that modeling milk production data without weighting data according to standard errors did not materially change interpretations presented below, which gives confidence to the relative homogeneity of the data. The mixed model procedure of SAS (SAS Institute, 1999) was used to assess effects of prepubertal ADG and BWC on milk production independent of genetic or management differences that were evident between trials. Linear and quadratic effects of prepubertal ADG and BWC and their combinations were modeled including a random classification variable for each trial. Initial values for the covariate parameters before optimization were their ordinary least squares estimates and variance components in the covariate structure, each used due to the limited amount of data resulting in difficulty fitting more complex random effects models. Plots presented are adjusted Y-value (St-Pierre, 2001) vs. prepubertal ADG. Total sum of squares for fixed effects components of the model was calculated by summing the squared difference of the adjusted response from the mean adjusted response. The error sum of squares is the residuals squared and coefficient of determination was calculated as residual sum of squares subtracted from total sum of squares for fixed effects components of the model divided by total sum of squares for fixed effects components of the model. Due to the presence of random effects, the R^2 values may actually be reduced when parameters are added to the fixed effects part of the model, in contrast to the only-increasing possibility in a fixed effects model; as such, significance of parameters will be emphasized, but R^2 values will be reported for comparison. The fit of each model was checked for heteroscedasticity by assessing the residual vs. predicted values plot and for normality by assessing the normal probability plot. Parameters were considered significant at

Table 1. Summary statistics of experiments included in the statistical analysis to determine optimal prepubertal average daily gain (ADG) for Holstein heifers.

Variable	n ¹	Mean	SD	Maximum	Minimum
Animals per treatment	21	22	25	85	4
ADG	21	839	140	1120	611
Milk production, kg/305-d	21	7493	1213	9873	5368
4.0% FCM, kg/305-d	21	7076	1002	9008	5577
Milk fat, %	21	3.65	0.29	4.26	3.32
Milk protein, %	18	3.33	0.10	3.47	3.15
Initial BW, kg	21	146	39	204	90
Final BW, kg ²	21	323	51	441	229
BW after calving, kg	21	516	24	550	477

¹Number of experimental treatments reporting the variable of interest and included in the statistical analysis.

²Final BW is the weight reported when the experimental growth treatment was terminated.

Table 2. Models with 1, 2, or 3 parameters for effects of average daily gain (ADG) and BW after calving (BWC) on first-lactation milk yield, FCM yield, milk fat, and milk protein for Holstein heifers grown at various prepubertal ADG.

One-parameter models													
Y =	Intercept	SE	P<	ADG	SE	P<	R ²						
305-d Milk, kg	8332	659	0.001	-0.874	0.606	0.175	0.059						
FCM, kg	7925	495	0.001	-0.897	0.417	0.052	0.242						
Fat, %	3.85	0.28	0.001	-0.000	0.000	0.452	0.054						
Fat, kg	303	18	0.001	-0.033	0.015	0.047	0.342						
Protein, %	3.33	0.12	0.001	0.000	0.000	0.975	0.000						
Protein, kg	254	22	0.001	-0.013	0.022	0.570	0.041						
BWC	551	22	0.001	-0.040	0.025	0.132	0.199						
Y =	Intercept	SE	P<	BWC	SE	P<	R ²						
305-d Milk, kg	1681	2974	0.589	11.430	5.692	0.068	0.370						
FCM, kg	1224	1977	0.555	11.492	3.772	0.010	0.611						
Fat, %	2.67	1.36	0.091	0.002	0.003	0.483	0.100						
Fat, kg	72	80	0.397	0.392	0.154	0.025	0.669						
Protein, %	3.07	0.54	0.001	0.001	0.001	0.639	0.048						
Protein, kg	97	109	0.409	0.284	0.211	0.209	0.358						
Two-parameter models													
Y =	Intercept	SE	P<	ADG	SE	P<	ADG ²	SE	P<	R ²			
305-d Milk, kg	1135	2816	0.699	16.727	6.750	0.031	-0.010	0.004	0.024	0.616			
FCM, kg	4362	2195	0.087	7.817	5.252	0.165	-0.005	0.003	0.124	0.539			
Fat, %	8.60	1.12	0.001	-0.012	0.003	0.001	0.000	0.000	0.001	0.683			
Fat, kg	219	83	0.033	0.168	0.196	0.408	-0.000	0.000	0.324	0.456			
Protein, %	4.31	0.69	0.001	-0.002	0.002	0.184	0.000	0.000	0.001	0.197			
Protein, kg	-79	66	0.281	0.786	0.155	0.001	-0.000	0.000	0.001	0.810			
BWC	670	140	0.002	-0.326	0.334	0.350	0.000	0.000	0.410	0.246			
Y =	Intercept	SE	P<	BWC	SE	P<	BWC ²	SE	P<	R ²			
305-d Milk, kg	13,322	48,251	0.790	-33.246	184.420	0.860	0.043	0.176	0.812	0.376			
FCM, kg	16271	21400	0.620	-46.079	119.930	0.708	0.055	0.114	0.640	0.614			
Fat, %	-24	24	0.348	0.105	0.092	0.277	-0.000	0.000	0.284	0.201			
Fat, kg	1506	1193	0.247	-5.187	4.638	0.287	0.005	0.005	0.255	0.726			
Protein, %	-7	10	0.523	0.039	0.039	0.347	-0.000	0.000	0.357	0.610			
Protein, kg	2132	1954	0.317	-7.713	7.642	0.339	0.008	0.007	0.321	0.525			
Three-parameter models													
Y =	Intercept	SE	P<	ADG	SE	P<	ADG ²	SE	P<	BWC	SE	P<	R ²
305-d Milk, kg	-8044	4486	0.116	21.764	6.424	0.007	-0.013	0.004	0.006	13.135	5.287	0.032	0.776
FCM, kg	-3877	3142	0.257	12.353	4.458	0.020	-0.007	0.003	0.016	11.784	3.718	0.010	0.813
Fat, %	8.43	1.83	0.002	-0.012	0.003	0.002	0.000	0.000	0.001	0.000	0.002	0.909	0.685
Fat, kg	-4	127	0.975	0.268	0.187	0.183	-0.000	0.000	0.151	0.341	0.155	0.052	0.759
Protein, %	3.98	0.97	0.006	-0.002	0.002	0.191	0.000	0.000	0.001	0.001	0.001	0.608	0.305
Protein, kg	-227	96	0.056	0.833	0.146	0.001	-0.000	0.000	0.001	0.244	0.121	0.078	0.868

$P < 0.05$ and were considered a tendency for significance at $P < 0.10$.

RESULTS AND DISCUSSION

Milk Production

Parameter estimates for various models are shown in Table 2 with corresponding standard errors, P -values, and R^2 . Results of the current literature analysis on effects of prepubertal ADG on first-lactation milk production in Holstein cows are consistent with results of previous reviews (Foldager and Sejrsen, 1987; Sejrsen et al., 2000) that milk yield is curvilinear in re-

sponse to the quadratic function of increasing ADG (Table 2; Figure 2). All parameters except the intercept were statistically different from zero and the coefficient of determination was 0.62, indicating that, after adjusting for differences between experiments, prepubertal ADG contributed significantly to variation between cows in first-lactation milk production. Increasing BWC tended ($P < 0.07$) to increase milk production in first lactation. These results are consistent with previous analyses (Keown and Everett, 1986); however, experiments included in this analysis have a relatively narrow spread in BWC (477 to 550 kg), which clearly limits interpretation of these results to the confines of this

Figure 2. Quadratic milk production response to changes in average daily gain (ADG) adjusted for the random effect of experimental trial. $305\text{-d Milk} = 1135 + 16.7278 \times \text{ADG} - 0.01047 \times \text{ADG}^2$; $R^2 = 0.616$.

Figure 3. Fat-corrected milk production response to changes in average daily gain (ADG) after adjustment for the random effect of trial. $\text{FCM} = 4362 + 7.817 \times \text{ADG} - 0.00518 \times \text{ADG}^2$; $R^2 = 0.53$.

range. The parameter relating ADG before puberty and BWC was not significantly different from zero, although the relationship was for heifers grown more rapidly before puberty to calve at reduced BW. Comparisons of the 2- and 3-parameter models, where BWC was included in addition to linear and quadratic effects of ADG, indicate that the majority of the effect was in shifting the intercept, although the fit was generally improved. Likewise, first-lactation milk production was not affected by an interaction between BWC and ADG. Fat-corrected milk followed a similar profile as uncorrected milk production; however, due to differences in milk fat concentration, there was a tendency ($P < 0.06$) for FCM to be decreased at increasing ADG, and the quadratic FCM response to prepubertal ADG was shifted to the left and dampened (Figure 3).

Milk production was maximal at a prepubertal ADG of 799 g/d using results of the 2-parameter quadratic model, or at 836 g/d for the model including BWC if heifers calved at a constant BW. Subsequent FCM production was maximal at ADG 755 g/d for models containing quadratic effects of ADG or 825 g/d when BWC was included in the model and was constant.

The quadratic response relating ADG to first-lactation milk yield, although generated from several experiments, does appear to have physiological relevance. First, the intercept was not statistically different from zero and fitting the model with an intercept that was forced through zero had minor effects on other param-

eters (maximum milk yield occurred at 805 vs. 799 g/d ADG). Although out of the range of these experiments, milk production would be expected to be zero at no growth. Secondly, assessing raw data from experiments that entered the analysis would appear to lead to a quadratic response in milk production if the intercept differences are ignored. Several experiments used 2 differing levels of ADG as treatments when testing effects on milk production. This practice is based on the assumption that the response to increasing ADG is a linear effect on mammary development and subsequent milk yield or the belief that maximizing differences in ADG would produce a maximal difference in milk production. The results of the present analysis show the problems associated with a limited number of treatments, because heifers from 2 treatments with large differences in ADG could produce equal amounts of milk simply because they are on a similar horizontal plane of the response curve or are too near the apex.

Both Stelwagen and Grieve (1992) and Van Amburgh et al. (1998) conducted experiments designed with capacity to test a potential quadratic effect of milk production response to increasing ADG; each observed significant linear effects only, but in opposing directions. The quadratic response to ADG is supported by results of Foldager and Sejrsen (1987), who reported that milk production was maximized at a prepubertal ADG between 600 and 700 g/d for large breed heifers, although

this is a substantially lower growth rate than the results obtained in the current analysis.

Due to the relatively low number of experiments in this analysis, there was a possibility that results of one experiment could dramatically affect results obtained from the analysis and materially change interpretation of the optimal growth rate for maximal production. Sensitivity analysis indicated that predicted maximum response did not change greatly based on results of any individual experiment (range of maximum milk occurring from an ADG of 763 to 847 g/d); however, strength of the relationship between prepubertal ADG and milk production was altered (although all slope parameters had $P < 0.15$). Where the "true" ADG for maximum milk production lies is also likely influenced by animal genetics, which reduces the probability that it is a fixed value (Sejrsen et al., 2000).

Reductions in circulating somatotropin have been considered as one mechanism of action for reduced mammary development in response to high levels of ADG (Sejrsen et al., 1983). More specifically, response to somatotropin may be indirectly mediated by biological availability of IGF-I (Berry et al., 2001). Presence of a quadratic response in milk production to increasing ADG, however, complicates interpretation of all aspects associated with effects of increasing ADG. For instance, Weber et al. (2000) found an interaction between bST treatment and growth rate on indicators of mammary development. Heifers in the low feeding group were fed to gain 550 g/d and the high group was fed to gain 1100 g/d. Comparison with Figure 2 would indicate that heifers fed on the high diet would have likely produced less milk than the low group if these heifers were followed through the first lactation; however, each group likely would have had submaximal levels of milk production. The presence of an interaction between ADG and bST may give an additional indication of the complexity of mammary gland development regulation. Mammary development for heifers fed for high ADG may respond to increasing growth hormone, whereas at low ADG, resulting from a relative nutritional insufficiency, the more dominant components may be those that are involved in sparing nutrients for maintenance functions at the expense of productive functions. Radcliff et al. (1997) did not observe an interaction in mammary tissue analyses conducted on heifers raised on low and high planes of nutrition (approximately 800 and 1200 g/d, respectively) and similar hormonal regimens. However, further analysis of systemic effects of somatotropin and nutritional plane indicated that circulating somatotropin removal as measured by the area under the curve and liver growth hormone receptor 1A mRNA were significantly affected by an interaction between feeding level and bST injection (Radcliff et al.,

2004). These results combine to support a hypothesis that changes in prepubertal ADG trigger different mechanisms that reduce mammary development at high and low ADG and that the cumulative effects of these mechanisms is minimal at an ADG near the point associated with highest milk production.

Milk Constituents

Milk protein yield was quadratically affected by alterations in prepubertal ADG (Table 2), and milk protein yield was maximized when prepubertal growth occurred at 836 g/d. Milk protein yield response to alterations in prepubertal ADG may be affected by the reduction in mammary ductal development that is characteristically observed during allometric growth (Tucker, 1987) and ultimately affects number of secretory alveoli. Although protein percentage was significantly affected by a quadratic response, parameters were very small and likely of little biological relevance. Adjusted protein yield was virtually identical to the protein that would be predicted based on a constant milk protein percentage. Increasing BWC tended to yield increasing amounts of protein when quadratic effects for ADG were included in the model and may indicate an improved ability to support lactation as well as requiring reduced growth during first lactation allowing a greater amount of nutrients to be used for milk protein synthesis.

Milk fat production was linearly increased by increases in BWC ($P < 0.03$). The response of milk fat production to changes in BWC have been observed previously (Dobos et al., 2001), but several other experiments in which BWC was altered by postpubertal ADG alterations did not show a significant relationship with milk fat production (Lacasse et al., 1993; Grummer et al., 1995; Hoffman et al., 1996). Each of those experiments had BWC that were greater than those found to maximize first-lactation milk production, whereas each of the experiments used in the current analysis had BWC lower than those recommendations (Keown and Everett, 1986), which may explain the differences in the current results.

An interesting finding of this analysis was that yield of milk fat seemed to remain relatively constant independent of alterations in prepubertal ADG, which occurred despite the significant quadratic effect observed for milk and milk protein yield. Although there is some variation observed in milk fat yield following prepubertal ADG manipulation, it is clear that response of milk fat to ADG is at least not as strong as response of total milk and milk protein yield. This relationship was observed by assessing effects of prepubertal ADG on adjusted milk fat production and the milk fat produc-

Figure 4. Effects of average daily gain (ADG) on adjusted first lactation milk fat production. Relationship represented by solid line indicates best-fit quadratic response after adjusting fat production by the random effect of trial. Relationship represented by dashed line is the regression line for fat production that would be expected based on adjusted milk production if milk fat concentration remained constant across ADG levels at 3.52%, which is the predicted minimum milk fat content. $Fat = 219 + 0.168 \times ADG - 0.00012 \times ADG^2$; $R^2 = 0.456$.

tion that would be predicted based on the adjusted milk production (Figure 4) at a constant milk fat percentage (3.52% fat, which was the minimum level of fat predicted from the quadratic ADG model in Table 2). Milk fat production remained relatively constant at differing prepubertal ADG whereas milk production varied significantly with alterations in prepubertal ADG, leading to the quadratic effect for milk fat concentration (Figure 5). The quadratic effect of prepubertal ADG on milk fat percentage was significant, which indicates that even when milk production is reduced, milk fat secretion may be enhanced to maintain similar yields of milk fat. Whereas milk fat yield was linearly decreased ($P < 0.05$) as prepubertal ADG increased, this effect may be due to the tendency for BWC to decrease as prepubertal ADG increases, because this parameter becomes insignificant ($P < 0.20$) when BWC is included as a covariate. The current analysis indicates that when prepubertal ADG is manipulated, differences in milk fat concentrations can occur, and these differences can be achieved independent of total milk and milk protein yield after adjusting for cow management and genetics.

Figure 5. Effects of prepubertal average daily gain (ADG) on adjusted first-lactation milk fat percentage. $Fat = 8.60 - 0.012 \times ADG + 0.000006652 \times ADG^2$; $R^2 = 0.683$.

CONCLUSIONS

Responses to alterations in prepubertal ADG are interpreted to indicate that there is a level of ADG where total milk and protein yield can be maximized, and this seems to occur around 800 g/d for Holstein heifers of a genetic merit similar to those reported in recent literature. However, fat yield was linearly affected by prepubertal ADG in contrast to the significant quadratic response seen for milk production. This occurred due to a significant quadratic response in milk fat percentage, indicating that when milk yield is reduced, milk fat concentration can be altered to yield similar levels of milk fat over the lactation. Yield responses to increasing BWC were generally increased, likely due to increased capacity for nutrient intake and reduced nutrient use for nonlactation purposes; however, experimental treatments in this analysis had a relatively small range in BWC. The results of this analysis indicate that, when raising dairy heifers for maximum first-lactation milk production, growth between approximately 150 to 320 kg of body weight growth should be limited to around 800 g/d.

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