Genetic regulation of prepartum dry matter intake in Holstein cows

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ABSTRACT

The objective of this study was to estimate genetic parameters for dry matter intake (DMI) in prepartum nonlactating and in lactating Holstein cows. Measurements were recorded on cows from Iowa State University (ISU) and the University of Florida (UF) dairy herds. Individual feed intake data were recorded daily at ISU from approximately 30 d prepartum through 150 d in milk (DIM). Individual intakes from cows at UF were recorded for approximately 42 d pre- and postpartum. Prepartum DMI traits were defined as DMI on d –15 (multiparous) or d –8 (primiparous) relative to calving date (DRYDMI), DMI on d –1 before parturition (CALVEDMI), and the negative of the slope of a regression line fitted through the last 14 (multiparous) or 7 (primiparous) days before calving (DEC). Lactation DMI traits were defined as DMI at 30 DIM (DMI30) and 100 DIM (DMI100; ISU data only). The final data set included 245 primiparous and 221 multiparous cows from ISU, and 125 multiparous cows from UF. Heritability estimates were 0.43, 0.64, 0.32, and 0.62 for DRYDMI, CALVEDMI, DEC, and DMI30, respectively. The estimate of heritability for DMI100 (ISU only) was 0.52. The genetic correlation between DRYDMI and DMI30 was 0.97. Thus, DMI prepartum is a moderately heritable trait that is highly correlated with intake during early lactation. Genetic correlations between DEC and DMI during lactation were lower and similar to standard error estimates (-0.24 ± 0.22 for DEC and DMI30 for combined data, and -0.13 ± 0.27 for DEC and DMI100 in ISU data). Thus, selection for altered DMI during lactation may not dramatically affect the depression in intake that occurs before parturition.

Key words: heritability, correlation, feed efficiency

INTRODUCTION

Feed efficiency is a critical factor in the economic and environmental sustainability of the dairy industry because feed costs account for more than half of the total production costs of dairy operations (USDA-ERS, 2014). Genetic selection and improved management methods have significantly increased milk production, resulting in increased feed intake and feed costs, but also improved feed efficiency. When commodity prices are especially high, feed costs cause major concern among producers. One approach to control these costs in an environmentally sustainable way is to select cows for improved feed efficiency.

To improve feed efficiency through selection, a thorough understanding of the genetic regulation of DMI is needed. Genetic parameters for feed intake have been estimated from various individual and pooled populations of lactating Holstein cattle, and the average heritability for DMI was 0.34 (Berry et al., 2014). Thus, the regulation of DMI has a strong genetic component, and selection on this trait will likely be successful. It is also important to consider DMI at different stages of lactation, as the relative effect of genes controlling DMI may vary throughout a lactation cycle. Estimates of genetic correlations between DMI measured at different times during lactation have a wide range, from 0.10 to 0.97 (Veerkamp and Thompson, 1999; Berry et al., 2007; Hüttmann et al., 2009; Buttchereit et al., 2011; Spurlock et al., 2012; Tetens et al., 2014). However, the genetic regulation of DMI during the nonlactating phase has received minimal attention to date, most likely because the dry period accounts for less than 60 d per year per cow. Also, because milk production is not occurring when cows are dry, production efficiency cannot be determined during this time. However, prepartum intake, especially during the final weeks of gestation, plays a crucial role in the upcoming lactation. The prepartum transition period is characterized by a sharp decline in DMI, and the magnitude of this decline may affect health and productivity after parturition (Grummer, 1995). It is therefore important to understand the genetic relationship between intake during nonlactating and lactating periods to fully appreciate potential con-

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sequences of selection for altered DMI during lactation, particularly as it relates to improved feed efficiency.

The objectives of the current study were to estimate heritability for prepartum intake traits and to investigate their genetic relationships with DMI during lactation.

MATERIALS AND METHODS

Animals and Data Collection

All animal experiments conducted at Iowa State University (ISU) were approved by the ISU Institutional Animal Care and Use Committee (Ames). Feed intake data were collected from a single lactation for 466 cows at the ISU Dairy Farm from March 2008 through November 2010. Cows ranged from parity 1 to parity 7. Feed intake data collection began approximately 30 d prepartum and continued through approximately 150 DIM. Cows on the study descend from 103 sires and 362 dams.

Cows were housed in group pens equipped with a Calan Broadbent Feeding system, and each cow was assigned a bin and trained to gain access only to that bin. A TMR was fed ad libitum once (during the dry period) or twice (during lactation) daily. The TMR was formulated to meet or exceed nutritional requirements as determined by the NRC (2001). Once a day, the refusals from each bin were removed. Both the quantity of feed dispensed and the feed reclaimed were recorded electronically to obtain daily intake. Samples of the TMR were taken 4 times per week and pooled to a weekly sample that was analyzed for DM content (Dairyland Laboratories Inc., Arcadia, WI). Daily DMI records were discarded if a cow consumed all feed provided on a particular day because it was not a fair representation of the feed consumed had the cow been fed ad libitum. This represented a small percentage (<3%) of the data. Data were also unavailable if a cow was removed from the pen for medical treatments. Cows were weighed and scored weekly for body condition (Elanco Animal Health, 1996) by a single trained evaluator.

Feed intake data were recorded for a total of 128 multiparous cows primarily during the summer months from August 2007 through October 2011 at the University of Florida (UF) Dairy Unit, as described by do Amaral et al. (2009, 2011), Tao et al. (2011, 2012), and Thompson et al. (2014). After editing, a total of 125 cows were included in analyses. Briefly, similar to ISU, cows were fed at UF using a Calan gate system, and feed amounts offered and refused were recorded daily during the dry period and lactation. Approximately half of the cows at UF were housed in a barn with no methods to alleviate heat stress, whereas the other

half were housed in a barn with cooling methods. All experimental procedures in the aforementioned studies were approved by the Animal Research Committee or the Institutional Animal Care and Use Committee of the University of Florida.

Definition of Dry Matter Intake Traits

To predict missing values and minimize day to day variation, smoothing splines were applied to the daily intake data using the PROC TRANSREG procedure and a smoothing parameter of 70 (SAS Institute, 1999). All analyses were done using data predicted from this procedure. Cows were excluded if they did not have 2 or more feed intake records 1 wk (primiparous) or 2 wk (multiparous) before parturition. Some cows did not have both pre- and postpartum data because intake was not recorded if a cow was undergoing treatment for a medical condition, and some cows did not continue on the study after parturition. The final ISU data set included 432 cows with prepartum and 400 cows with postpartum data, whereas the final UF data set included 125 cows with prepartum and 103 with postpartum data.

Multiple traits were defined to characterize DMI at different stages before and after parturition. Intake during the dry period was represented by DRYDMI, defined as DMI on the day before initiation of the rapid decline in feed intake that precedes parturition. For primiparous cows, DRYDMI was represented by d -8 relative to parturition (d 0); for multiparous animals, DRYDMI was represented by d -15. Intake immediately before calving (CALVEDMI) was DMI on d -1 for all cows. The decrease in intake before parturition (DEC) was calculated as the slope of the regression line fit through the daily DMI before parturition. The negative of this slope was used in calculations so that greater values corresponded to larger declines in intake. The regression for primiparous cows was fitted for d -7 through -1 while the regression was fitted through d -14 through -1 for multiparous cows. Similarly, INC represented the rate of increase in DMI after parturition and was calculated as the slope of the regression line fitted through d 1 to 21 postpartum. The INC data were omitted from individuals who lacked data during the first 21 DIM due to illness or other reasons. The DMI at 30 DIM (DMI30) was chosen to represent a point in early lactation, but after the transition period, DMI at 100 DIM (DMI100) was selected as a time when lactating cows had returned to positive energy balance, on average (Spurlock et al., 2012). Dry matter intake at 100 DIM could only be calculated for the ISU cows because intake records for cows at UF ended at approximately 42 d after calving.

Genetic Analysis

Heritabilities and genetic correlations were estimated using ASReml software (Gilmour et al., 2008). Fixed effects included parity (1, 2, or 3 through 7), calving age (divided into 7 groups based on parity and age), year-season of calving [year, 2007 through 2011; season as winter (December to February), spring (March to May), summer (June to August), and fall (September to November)], calf sex (male, female, or twins), and live or dead status of the calf. When the ISU and UF data were combined, farm (1 or 2) and treatment (ISU, UF with cooling, or UF without cooling) were also included as fixed effects. The model for analysis was

$$y_i = \mu + lac_i + calveage_i + seasalv_i + calf_i + status_i + a_i + e_i,$$

where y_i = individual phenotype; μ = overall mean; lac_i = fixed effect of lactation (1 to 3) for cow i ; $calveage_i$ = fixed effect of age at calving class (1 to 7) for cow i ; $seasalv_i$ = fixed effect of year and season of calving (1 to 12) for cow i ; $calf_i$ = fixed effect of calf sex (1 to 3) of cow i ; $status_i$ = fixed effect of born dead or alive (1 or 2) for cow i ; a_i = additive genetic effect for the i th cow; and e_i = random residual error. To calculate the genetic and phenotypic correlations among the traits, the model was extended to be a multivariate model. A 5-generation pedigree was used that included 3,156 individuals for the ISU data set, 1,880 individuals for the UF data set, and 4,358 individuals when combined.

RESULTS AND DISCUSSION

Intake traits are summarized in Table 1 for all cows. Intake was relatively stable from 30 to 15 d prepartum and then gradually declined as parturition approached (Figure 1). As expected, multiparous cows ate more

than primiparous cows, on average. This is likely due to differences in BW, as multiparous cows from ISU and UF were larger than primiparous cows by 109 and 64 kg, respectively (Table 2). In addition, multiparous cows from UF that were housed in facilities without cooling ate less than multiparous cows housed in facilities with cooling (Figure 1). Body condition scores were similar between primiparous and multiparous cows from ISU, but cows from UF were much less conditioned than ISU cows (Table 2). The depression of DMI as parturition approaches is also evident in Figure 1. On average, DMI of multiparous cows began to decline approximately 2 wk before calving with the sharpest decline occurring during the last week, whereas DMI of primiparous cows sharply declined beginning −7 DIM. This observed pattern is consistent with Hayirli et al. (2002), who found that primiparous cows had consistent DMI until the week before calving, whereas older cows experienced a more gradual decline in DMI. During the final 2 wk of gestation in the current study, DMI of primiparous cows decreased by 13%, with 77% of that occurring during the final week of gestation. Also, multiparous ISU cows decreased DMI by 15% during the final 2 wk, with 72% of that decrease occurring during the week before calving. The UF cows had the greatest decrease in DMI. The DMI of cows housed in facilities without cooling declined 24% during the final 2 wk, whereas the DMI of cows housed in facilities with cooling declined 22% in the 2 wk before parturition. A reason for the differences in DMI between ISU multiparous and UF multiparous cooled cows could be that animals from UF were more likely to be experiencing some level of heat stress, as almost all UF data were collected during the summer months. The declines in DMI observed in this study are less than those reported by Hayirli et al. (2002) and Marquardt et al. (1977), who observed decreases in DMI between 32.2 and 52%.

Heritability estimates and correlations for the ISU data and for the combined data set are shown in Tables

Table 1. Number of records (n) and the mean, standard deviation, minimum, and maximum values for feed intake traits

Trait ¹	n	Mean (kg)	SD	Minimum	Maximum
DRYDMI	557	11.37	2.11	4.09	17.15
CALVEDMI	557	10.04	2.56	2.44	18.39
DEC	557	0.12	0.17	0.86	−0.44
DMI30	503	19.91	3.48	6.74	31.20
DMI100 ²	400	23.74	3.39	15.09	32.91
INC	459	0.33	0.22	−0.54	1.23

¹DRYDMI = DMI d −8 (primiparous) or d −15 (multiparous) relative to parturition; CALVEDMI = DMI on d −1 relative to parturition; DEC = the negative of the slope of the regression line fitted through daily DMI before parturition; DMI30 = DMI 30 d postpartum; DMI100 = DMI 100 d postpartum; INC = the rate of increase in DMI after parturition calculated as the slope of the regression line fitted through DMI on d 1 to 21 postpartum.

²Records on Iowa State University cows only.

Figure 1. Average daily DMI during the last 30 d prepartum through the first 30 d postpartum (–30 to 30 DIM) is shown for primiparous (diamonds) and multiparous (triangles) cows from the Iowa State University herd, and for multiparous cows housed in facilities with (+) and without (×) cooling from the University of Florida herd.

3 and 4, respectively. Dry matter intake during the prepartum period was moderately to highly heritable, and heritability estimates for DMI measured during the dry period and lactation were similar. The estimates for lactating DMI were similar to monthly averages reported by Spurlock et al. (2012) for the same population, which ranged from 0.22 to 0.60 for the first 5 mo of lactation. In general, estimates of DMI heritability were similar to or slightly higher than those reported in the literature, which range from 0.04 to 0.54 (Veerkamp and Thompson, 1999; Coffey et al., 2001; Hüttmann et al., 2009; Buttchereit et al., 2011; Spurlock et al., 2012; Tetens et al., 2014). Many of these previous studies only used records for primiparous animals (Veerkamp and Thompson, 1999; Coffey et al., 2001; Hüttmann et al., 2009; Buttchereit et al., 2011; Tetens et al., 2014),

population sizes were variable (289 to 910 animals), and a variety of statistical approaches was used to estimate DMI heritability. All of these factors may contribute to the range in estimates found in current literature. Estimates of DRYDMI (0.04 ± 0.47), CALVEDMI (0.00), and DMI30 (0.00) heritability did not converge or were not different from zero for the UF data alone, most likely the result of a relatively small data set. Estimates of genetic correlations between intake traits ranged from 0.24 to 0.97 in the combined data set (Table 4). Most notably, the correlations of DRYDMI and CALVEDMI with DMI30 were 0.97 and 0.74, respectively. In the ISU data set, the correlation between DRYDMI and DMI100 was also high (0.86). These correlations suggest that DMI in the dry period is under similar genetic regulation as DMI during early lacta-

Table 2. Number of animals (n) and their average BCS and BW during their nonlactating prepartum period, and at 30 and 100 DIM

Item	n	BCS			BW		
		Prepartum	30 DIM	100 DIM	Prepartum	30 DIM	100 DIM
ISU							
Parity 1	245	4.34 ± 0.25	3.63 ± 0.44	3.33 ± 0.48	647 ± 60	551 ± 55	548 ± 48
Parity 2+	221	4.23 ± 0.37	3.47 ± 0.58	2.99 ± 0.61	756 ± 79	637 ± 62	623 ± 55
UF							
Parity 2+	125	3.52 ± 0.44	3.17 ± 0.41	—	711 ± 79	621 ± 60	—

¹Data are summarized for primiparous and multiparous cows from the Iowa State University (ISU) and University of Florida (UF) dairy herds and presented as the mean ± SD.

Table 3. Heritability estimates (SE) and correlations (SE) for intake traits based on data collected from cows at Iowa State University¹

Trait ²	DRYDMI	CALVEDMI	DEC	DMI30	DMI100
DRYDMI	0.40 (0.11)	0.91 (0.08)	−0.52 (0.31)	0.90 (0.12)	0.86 (0.17)
CALVEDMI	0.66 (0.03)	0.62 (0.11)	−0.81 (0.13)	0.73 (0.12)	0.62 (0.15)
DEC	0.15 (0.05)	−0.59 (0.03)	−0.25 (0.11)	−0.30 (0.24)	−0.13 (0.27)
DMI30	0.40 (0.05)	0.45 (0.05)	−0.16 (0.05)	0.65 (0.13)	0.95 (0.07)
DMI100	0.30 (0.05)	0.30 (0.05)	−0.08 (0.06)	0.70 (0.03)	0.52 (0.13)

¹Heritability estimates are shown on the diagonal, genetic correlations above the diagonal, and phenotypic correlations below the diagonal.

²DRYDMI = DMI d −8 (primiparous) or d −15 (multiparous) relative to parturition; CALVEDMI = DMI on d −1 relative to parturition; DEC = the negative of the slope of the regression line fitted through daily DMI before parturition; DMI30 = DMI 30 d postpartum; DMI100 = DMI 100 d postpartum.

tion. Positive estimates of genetic correlations in the literature between different stages of lactation range from 0.10 to 0.97 (Veerkamp and Thompson, 1999; Berry et al., 2007; Hüttmann et al., 2009; Buttchereit et al., 2011; Spurlock et al., 2012; Tetens et al., 2014). In general, the correlations are strong between time points that are close together, and weak as the interval grows larger, leading others (Koenen and Veerkamp, 1998; Berry et al., 2007; Hüttmann et al., 2009; Tetens et al., 2014) to suggest that the genetic regulation of DMI differs with stage of lactation. In particular, Manzanilla Pech et al. (2014) found that DMI at 10 DIM was lowly to negatively correlated with DMI measured in mid and late lactation, leading to the conclusion that DMI is genetically different in early compared with mid lactation. However, Spurlock et al. (2012) found correlations above 0.70 for DMI measured in the first 5 mo of lactation. Thus, at least in this ISU population, the genetic regulation of DMI appears to be consistent throughout the dry period and first half of lactation.

Estimated genetic parameters for DEC and INC were lower than for actual intake traits. The INC was not heritable in this data set (0.62 ± 0.62 for UF data; 0.00 for ISU and combined data), whereas DEC was moderately heritable (Tables 3 and 4). Genetic correlations between DEC and other intake traits in the combined data set were −0.24 to −0.81, with the highest correlation between DEC and CALVEDMI. Phenotypic correlations were lower (0.13 to −0.63). The magnitude

of decline in feed intake before parturition has been associated with metabolic disorders postpartum (Grummer et al., 2004). Thus, it is important to define how selection for DMI during lactation may affect DEC at both the genetic and phenotypic levels. Although the population used to investigate these correlations in the current study was relatively small, moderate (−0.24) and low (−0.15) genetic and phenotypic correlations, respectively, were estimated from the combined data set between DEC and DMI30. In the ISU population estimates for genetic and phenotypic correlations between DEC and DMI100 were slightly lower than those for DEC and DMI30 (−0.13 and −0.08, respectively). However, it should be noted that estimates of genetic and phenotypic correlations involving DEC were less than or similar to standard error estimates in all cases (Tables 3 and 4). These genetic correlations are particularly important because they indicate that selection for altered feed intake during lactation may not influence the decline in DMI before parturition. This implies that selection for decreased DMI during lactation, used as a strategy to improve feed efficiency, will likely not contribute to an exaggerated decrease in DMI before parturition. Because the decline in intake, rather than the level of DMI, contributes to metabolic issues after parturition in most cases (Grummer et al., 2004), the current research indicates selection for reduced DMI during lactation may not have a dramatic deleterious effect on metabolic health during the transition period.

Table 4. Heritability estimates (SE) and correlations (SE) for intake traits based on data collected at Iowa State University and the University of Florida¹

Trait ²	DRYDMI	CALVEDMI	DEC	DMI30
DRYDMI	0.43 (0.11)	0.85 (0.08)	−0.40 (0.26)	0.97 (0.11)
CALVEDMI	0.64 (0.03)	0.64 (0.11)	−0.81 (0.10)	0.74 (0.12)
DEC	0.13 (0.05)	−0.63 (0.03)	−0.32 (0.11)	−0.24 (0.22)
DMI30	0.40 (0.04)	0.43 (0.04)	−0.15 (0.05)	0.62 (0.13)

¹Heritability estimates are shown on the diagonal, genetic correlations above the diagonal, and phenotypic correlations below the diagonal.

²DRYDMI = DMI d −8 (primiparous) or d −15 (multiparous) relative to parturition; CALVEDMI = DMI on d −1 relative to parturition; DEC = the negative of the slope of the regression line fitted through daily DMI before parturition; DMI30 = DMI 30 d postpartum; DMI100 = DMI 100 d postpartum.

CONCLUSIONS

Intake during the prepartum period is a moderately heritable trait that is genetically similar to DMI during early lactation. Correlations between DMI and intake depression before calving suggest that selection against DMI as a strategy for improved feed efficiency may not have a large effect on the magnitude of intake depression that occurs before parturition. However, selection for reduced feed intake during lactation will likely contribute to a reduced DMI before calving.

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REFERENCES

- Berry, D. P., M. P. Coffey, J. E. Pryce, Y. deHaas, P. Lovendahl, N. Krattenmacher, J. J. Crowley, Z. Wang, D. Spurlock, K. Weigel, K. MacDonald, and R. F. Veerkamp. 2014. International genetic evaluations for feed intake in dairy cattle through the collation of data from multiple sources. *J. Dairy Sci.* 97:3894–3905.
- Berry, D. P., B. Horan, M. O'Donovan, F. Buckley, E. Kennedy, M. McEvoy, and P. Dillon. 2007. Genetics of grass dry matter intake, energy balance, and digestibility in grazing Irish dairy cows. *J. Dairy Sci.* 90:4835–4845.
- Buttchereit, N., E. Stamer, W. Junge, and G. Thaller. 2011. Short communication: Genetic relationships among daily energy balance, feed intake, body condition score, and fat to protein ratio of milk in dairy cows. *J. Dairy Sci.* 94:1586–1591.
- Coffey, M. P., G. C. Emmans, and S. Brotherstone. 2001. Genetic evaluation of dairy bulls for energy balance traits using random regression models. *Anim. Sci.* 73:29–40.
- do Amaral, B. C., E. E. Connor, S. Tao, J. Hayen, J. Bubolz, and G. E. Dahl. 2009. Heat-stress abatement during the dry period: Does cooling improve transition into lactation? *J. Dairy Sci.* 92:5988–5999.
- do Amaral, B. C., E. E. Connor, S. Tao, J. Hayen, J. W. Bubolz, and G. E. Dahl. 2011. Heat stress abatement during the dry period influences metabolic gene expression and improves immune status in the transition period of dairy cows. *J. Dairy Sci.* 94:86–96.
- Gilmour, A. R., B. J. Gogel, B. R. Cullis, and R. Thompson. 2008. *ASReml User Guide*. Release 3.0. VSN International Ltd., Essex, UK.
- Grummer, R. R. 1995. Impact of changes in organic nutrient metabolism on feeding the transition dairy cow. *J. Anim. Sci.* 73:2820–2833.
- Grummer, R. R., D. G. Mashek, and A. Hayirli. 2004. Dry matter intake and energy balance in the transition period. *Vet. Clin. Food. Anim.* 20:447–470.
- Hayirli, A., R. R. Grummer, E. V. Nordheim, and P. M. Crump. 2002. Animal and dietary factors affecting feed intake during the pre-fresh transition period in Holsteins. *J. Dairy Sci.* 85:3430–3443.
- Health, E. A. 1996. Body condition scoring in dairy cattle. A1:8478. Elanco Animal Health, Greenfield, IN.
- Hüttmann, H., E. Stamer, W. Junge, G. Thaller, and E. Kalm. 2009. Analysis of feed intake and energy balance of high-yielding first lactating Holstein cows with fixed and random regression models. *Animal* 3:181–188.
- Koenen, E. P. C., and R. F. Veerkamp. 1998. Genetic covariance functions for live weight, condition score, and dry-matter intake measured at different lactation stages of Holstein Friesian heifers. *Livest. Prod. Sci.* 57:67–77.
- Manzanilla Pech, C. I. V., R. F. Veerkamp, M. P. L. Calus, J. E. Pryce, and Y. De Haas. 2014. Genetic parameters and accuracy of recording dry matter intake in first parity Holstein-Friesian cows. *Proc. 10th World Congress on Genetics Applied to Livestock Production (WCGALP)*, Vancouver, BC, Canada. <https://event.crowdcompass.com/wcgalp2014/activity/dPDGxDu6ri>.
- Marquardt, J. P., R. L. Horst, and N. A. Jorgensen. 1977. Effect of parity on dry matter intake at parturition in dairy cattle. *J. Dairy Sci.* 60:929–934.
- NRC. 2001. *Nutrient Requirements of Dairy Cattle*. 7th ed. Natl. Acad. Press, Washington, DC.
- SAS Institute. 1999. *SAS/STAT User's Guide*. SAS Institute Inc., Cary, NC.
- Spurlock, D. M., J. C. M. Dekkers, R. Fernando, D. A. Koltes, and A. Wolc. 2012. Genetic parameters for energy balance, feed efficiency, and related traits in Holstein cattle. *J. Dairy Sci.* 95:5393–5402.
- Tao, S., J. W. Bubolz, B. C. do Amaral, I. M. Thompson, M. J. Hayen, S. E. Johnson, and G. E. Dahl. 2011. Effect of heat stress during the dry period on mammary gland development. *J. Dairy Sci.* 94:5976–5986.
- Tao, S., I. M. Thompson, A. P. A. Monteiro, M. J. Hayen, L. J. Young, and G. E. Dahl. 2012. Effect of cooling heat-stressed dairy cows during the dry period on insulin response. *J. Dairy Sci.* 95:5035–5046.
- Tetens, J., G. Thaller, and N. Krattenmacher. 2014. Genetic and genomic dissection of dry matter intake at different lactation stages in primiparous Holstein cows. *J. Dairy Sci.* 97:520–531.
- Thompson, I. M. T., S. Tao, A. P. A. Monteiro, K. C. Jeong, and G. E. Dahl. 2014. Effect of cooling during the dry period on immune response after *Streptococcus uberis* intramammary infection challenge of dairy cows. *J. Dairy Sci.* 97:7426–7436.
- USDA-ERS (US Department of Agriculture-Economic Research Service). 2014. Milk cost of production estimates. Accessed Jul. 1, 2014. <http://www.ers.usda.gov/data-products/milk-cost-of-production-estimates.aspx#.U768OvldWH5>.
- Veerkamp, R. F., and R. Thompson. 1999. A covariance function for feed intake, live weight, and milk yield estimated using a random regression model. *J. Dairy Sci.* 82:1565–1573.