



Lactation curves of Montbéliarde-sired and Viking Red-sired crossbred cows and their Holstein herdmates in commercial dairies

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ABSTRACT

Lactation curves were estimated for Montbéliarde (MO) × Holstein (HO) and Viking Red (VR) × HO 2-breed crossbred cows and for MO × VR/HO and VR × MO/HO 3-breed crossbred cows and their HO herdmates from test-day observations in 7 high-performance herds that participated in a designed study. Cows calved from 2010 to 2017. Test-day observations from milk recording were used to fit the lactation curves of cows in their first 3 lactations. Lactations of cows were required to have at least 250 DIM and to have at least 6 test days ≤265 DIM. Lactation curves from random regression (RR) were compared for 305-d production (kg), peak production (kg), peak day of production, and production from 4 to 103 DIM (kg), from 104 to 205 DIM (kg), and from 206 to 305 DIM (kg) for milk, fat, and protein. Also, the persistency of production was compared. First-lactation versus second- and third-lactation cows were analyzed separately for both the 2-breed and 3-breed crossbred cows and their respective HO herdmates. Legendre polynomial RR had the best goodness of fit for the lactation curves compared with Ali-Schaeffer and Wilmink RR from the test-day observations of milk, fat, and protein production. For fluid milk production of first-lactation cows, the MO × HO 2-breed crossbreds were not different from their HO herdmates for any of the lactation-curve characteristics, except persistency. However, the VR × HO 2-breed crossbreds had less fluid milk production compared with their HO herdmates. For first lactation, the MO × HO 2-breed crossbreds had more persistency of milk, fat, and protein production compared with their HO herdmates. The first-lactation MO × VR/HO 3-breed crossbreds had more persistency of fluid milk production compared with their HO herdmates. For second and third lactations, both the MO × HO and the VR × HO 2-breed crossbreds had higher fat production compared with

their HO herdmates. Furthermore, the MO × HO 2-breed crossbreds had more protein production (kg) in all 3 periods of lactation compared with their HO herdmates. Crossbred cows may have advantages over HO cows for persistency of production in high-performance herds.

Key words: crossbreeding, lactation curve, persistency

INTRODUCTION

For many years, the test interval method (TIM) was used to estimate 305-d production from test-day observations of milk, fat, and protein from milk recording for genetic evaluation of production in the United States (Voelker, 1981). The TIM divided the time between test days into 2 periods with an equal number of DIM. Production from the previous test day was assigned to the first period, and production from the subsequent test day was assigned to the later period (Sargent et al., 1968). In the 1990s, extensive research was conducted to improve the estimation of 305-d production for use in genetic evaluation. In particular, Schaeffer and Dekkers (1994) developed a test-day model using random regression (RR) that replaced TIM for Canadian estimation of 305-d lactations for genetic evaluation in 2000. Many countries globally followed the lead of Canada and have continued to use RR for estimating 305-d production from test-day observations. Use of RR permits the estimation of a unique lactation curve for each cow (Schaeffer, 2016).

Persistency measures the ability of a cow to maintain daily production following peak production (Wood, 1967). Gengler (1996) categorized the 3 most common measures of persistency of production as (1) ratios of partial or total production, (2) variation of test-day observations, or (3) mathematical models of lactation curves. Regardless of the measure of persistency used, a cow with more persistency of production will have a more horizontal lactation curve compared with a cow with less persistency of production (Togashi and Lin, 2003). Other studies have reported cows with more persistency of production have improved feed efficiency when fed roughages (Sölkner and Fuchs, 1987), less incidence of

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disease (Appuhamy et al., 2007), and improved reproductive performance (Muir et al., 2004) compared with cows with less persistency of production. Therefore, selection for more persistency of production could result in improved profitability of dairy cows. In an Iranian study, Elahi Torshizi and Hosseinpour Mashhadi (2018) recommended the use of RR genetic evaluation for persistency of production because RR provides more flexibility for the shape of lactation curves and results in higher heritability for persistency of production.

Dechow and Hansen (2017) recommended a 3-breed rotation of Alpine, Nordic Red, and Holstein (HO) breeds for commercial milk production when implementing a crossbreeding program in high-input, temperate environments. The Alpine breeds include Montbéliarde, Fleckvieh, and Brown Swiss. The Nordic Red breeds include Viking Red (VR), Norwegian Red, German Angler, and Aussie Red. In recent years, the Montbéliarde (MO), VR, and HO breeds have been marketed for 3-breed rotational crossbreeding (ProCROSS) by Coopex Montbéliarde (Roulans, France) and Viking Genetics (Randers, Denmark), and this 3-breed rotation continues to grow in popularity globally. The MO and VR breeds have placed more selection emphasis on fertility, health, and longevity for decades than has the HO breed while maintaining substantial selection emphasis on increased milk solids (Montbéliarde Association, 2019; Nordic Cattle Genetic Evaluation, 2019).

Hazel et al. (2017) reported MO × HO 2-breed crossbreeds had more fat plus protein production (kg) and VR × HO 2-breed crossbreeds had similar fat plus protein production (kg) compared with their HO herdmatres during first lactation. In more recent studies, Shonka-Martin et al. (2019) and Pereira et al. (2022) found 3-breed crossbreeds of the MO, VR, and HO breeds did not differ from their HO herdmatres for fat plus protein production (kg) from 4 to 150 DIM. Research on lactation-curve characteristics of crossbred dairy cows is very limited. Also, the persistency of production for MO-sired and VR-sired crossbred cows compared with their HO herdmatres has not been studied.

The objective of this research was to compare the lactation-curve characteristics and persistency of production for MO-sired and VR-sired crossbred cows compared with their HO herdmatres estimated from test-day observations using RR.

MATERIALS AND METHODS

Description of Cows and Herds

All procedures involving animal care and management were approved by the University of Minnesota Institutional Animal Care and Use Committee. Two generations

of crossbred cows and their HO herdmatres from 7 high-production herds in Minnesota were studied from a 10-yr field study (Hazel et al., 2017). Cows were housed in either a 4- or 6-row freestall barn and fed a TMR. At the conclusion of the study, the mean herd size was 982 ± 203 cows and the weighted mean production of cows across breed groups was $13,587 \pm 353$ kg of milk, 512 ± 9 kg of fat, and 426 ± 10 kg of protein. Foundation HO females were enrolled in 2008 and paired for mating by AI to MO, VR, or HO bulls. The HO cows and heifers were mated to HO bulls so that inbreeding was minimized. For HO service sires, the herds used only progeny-proven bulls marketed by Select Sires Inc. (Plain City, OH), and the herds were asked to choose HO bulls that ranked in the top 10% for net merit (VanRaden et al., 2018) at the time of selection. The MO and VR progeny-proven bulls were imported to the United States by Creative Genetics of California and ranked highly on the French Unique Synthesis Index (Montbéliarde Association, 2019) or the Nordic total merit index (Nordic Cattle Genetic Evaluation, 2019), which are the national selection indices for the MO and VR breeds, respectively.

The MO × HO and VR × HO 2-breed crossbred cows and their HO herdmatres initiated first lactation from January 2011 to April 2017. The MO × VR/HO and VR × MO/HO 3-breed crossbred cows were daughters of the 2-breed crossbred cows. The 3-breed crossbred cows and their HO herdmatres initiated first lactation from November 2012 to April 2017.

Data

The test-day observations from milk recording for crossbred cows and their HO herdmatres were analyzed in first, second, and third lactations. The initial data included 9,749 lactations (4,583 first, 3,285 second, and 1,881 third) of cows. Lactations of cows that calved with less than 260 d of gestation were removed ($n = 110$). All lactations of cows were required to have completed at least 250 DIM to eliminate potentially abnormal cows with short or incomplete lactations ($n = 1,619$). Cows were also required to have at least 6 test days from 4 to 265 DIM to avoid lengthy intervals between test days across 305-d lactations. Test days with fewer than 4 DIM or greater than 305 DIM were excluded, and each test day was required to have an observation for milk, fat, and protein production. Test-day observations were also required to have at least 1.0% and no greater than 9.0% fat and at least 1.0% and no greater than 6.0% protein (Heins et al., 2006).

Data were assigned to a herd-year-season (HYS) of calving within each lactation number. The HYS were 4-mo periods (January to April, May to August, and September to December) within each herd. Lactations of cows were

edited so that at least 3 crossbred and 3 HO herdmates were represented within each HYS for comparison of breed groups in the same herd by lactation number. Also, any HYS that had fewer than 3 cows of either crossbred breed group were combined with the contiguous HYS within herd and lactation number that had the fewest number of cows in a breed group. Following HYS edits, the cows in second and third lactation were combined to form a second- and third-lactation group. After all edits for 2-breed crossbred cows, 524 MO × HO and 548 VR × HO first lactations were compared with 1,073 first lactations of their HO herdmates, and 650 MO × HO and 633 VR × HO second and third lactations were compared with 1,223 second and third lactations of their HO herdmates. For 3-breed crossbred cows, 430 MO × VR/HO and 479 VR × MO/HO first lactations were compared with 1,043 first lactations of their HO herdmates, and 399 MO × VR/HO and 431 VR × MO/HO second and third lactations were compared with 827 lactations of their HO herdmates.

Estimation of Production

Initially, the 305-d lactation curves for milk, fat, and protein of each cow were estimated with 3 alternative RR functions: (1) Ali–Schaeffer, (2) Wilmink, and (3) Legendre polynomial of the third order (Oliveira et al., 2019). The Ali–Schaeffer RR function (Ali and Schaeffer, 1987) included coefficients for peak production, increasing production during lactation, and decreasing production during lactation as follows:

$$y_{ti} = (\beta_0 + \beta_1 Z_1 + \beta_2 Z_2 + \beta_3 Z_3 + \beta_4 Z_4) + (\alpha_{0i} + \alpha_{1i} Z_1 + \alpha_{2i} Z_2 + \alpha_{3i} Z_3 + \alpha_{4i} Z_4) + e_{ti},$$

where y_{ti} is the test-day record of cow i made on DIM t , e_{ti} is the random residual for cow i at day t , β_j is the fixed regression coefficient j , α_{ji} is the RR coefficient j for cow i , $Z_1 = t$, $Z_2 = t^2$, $Z_3 = \log(1/t)$ and $Z_4 = \log(1/t)^2$.

The Wilmink RR function (Wilmink, 1987) included coefficients for level of production at the start of the lactation, increasing production before peak, and decreasing production after peak, represented as follows:

$$y_{ti} = (\beta_0 + \beta_1 W_1 + \beta_2 W_2) + (\alpha_{0i} + \alpha_{1i} W_1 + \alpha_{2i} W_2) + e_{ti},$$

where $W_1 = t$ and $W_2 = \exp(-0.05t)$.

The Legendre polynomial RR function was described by Kirkpatrick et al. (1990) of the third order as follows:

$$y_{ti} = (\beta_0 P_0 + \beta_1 P_{1t} + \beta_2 P_{2t} + \beta_3 P_{3t}) + (\alpha_{0i} P_0 + \alpha_{1i} P_{1t} + \alpha_{2i} P_{2t} + \alpha_{3i} P_{3t}) + e_{ti},$$

where coefficients of the Legendre polynomial at day t were calculated as $P_{0t} = 1$, $P_{1t} = x$, $P_{2t} = \frac{1}{2}(3x^2 - 1)$, and $P_{3t} = \frac{1}{2}(5x^3 - 3x)$, where $x = -1 + 2 \frac{(t-1)}{(1-305)}$.

The estimates of β and α variables were obtained using the MIXED procedure of SAS version 9.4 (SAS Institute Inc., Cary, NC). The polynomials of order 2, 4, 5, and 6 were tested. Based on the Akaike's information criterion (AIC; smallest is best), a polynomial of third order was considered the best fit for modeling lactation curves of milk, fat, and protein for 305-d lactations.

A major difference between the 3 alternative RR functions is the number of parameters for each function. The Wilmink function has only 3 parameters compared with the 5 parameters of the Ali–Schaeffer and 4 parameters of the Legendre polynomial functions. The larger number of parameters for the Ali–Schaeffer and Legendre polynomial functions allow them to estimate a wider range of shapes for lactation curves than the Wilmink function (Macciotta et al., 2005). The Legendre polynomial function has been more widely used than the Ali–Schaeffer function to estimate 305-d production for genetic evaluation globally because of lower correlations among the parameter estimates (Schaeffer, 2016).

Lactation curves for each of the 5 breed groups (MO × HO, VR × HO, MO × VR/HO, VR × MO/HO, and HO) in this study were estimated with each of the 3 RR functions separately for first lactation as well as second and third lactations.

Goodness of Fit for the Alternative RR Across Breed Groups

The mean square prediction error (MSPE) was the measure of goodness of fit to assess which of the 3 RR functions best estimated daily production of milk, fat, and protein compared from actual test-day observations of milk, fat, and protein:

$$MSPE = \sum_{i=1}^n (O_i - E_i)^2 / n,$$

where $i = 1, 2, \dots, n$, and n is the number of test-day observations, and O_i and E_i represent observed and estimated production, respectively (Val-Arreola et al., 2004). A lower MSPE indicated a better goodness of fit for estimation of production among the 3 RR functions.

Akaike's and Schwarz's Bayesian information criteria (BIC) were also compared for the 3 RR functions.

Description of Comparative Traits

Lactation-Curve Characteristics. Daily production was estimated with the 3 alternative RR functions from test-day observations. The estimated daily production from each of the 3 alternative RR functions were summed to estimate 305-d milk, fat, and protein production. Peak production and DIM of peak production were obtained from the maximum of estimated daily production of milk, fat, or protein. Furthermore, milk, fat, and protein production were stratified into 3 periods of lactation, (1) the initial 100 DIM (4–103 DIM), (2) the middle 102 DIM (104–205 DIM), and (3) the final 100 DIM (206–305 DIM), to assess whether breed groups differed for production in these 3 stratified periods.

Persistency of Production. Persistency was defined as production in the final 100 DIM (206–305 DIM) minus production in the initial 100 DIM (4–103 DIM). A positive persistency indicated a cow had less production in the initial 100 DIM compared with the final 100 DIM, and a negative persistency indicated a cow had more production in the initial 100 DIM compared with the final 100 DIM. Therefore, a positive persistency indicated more persistency of production throughout the lactation (Jiang et al., 2020).

Statistical Analysis

Lactation-curve characteristics of production were estimated using the 3 RR functions, and the first-lactation and second- and third-lactation cows were analyzed separately for both 2- and 3-breed crossbred cows and their respective HO herdmates. The 2-breed crossbred cows were compared only with their HO herdmates that calved during the same lactation and HYS and, likewise, the 3-breed crossbred cows were compared only with their HO herdmates that calved during the same lactation and HYS. Most of the HO herdmates of the 2-breed crossbred cows were from a previous generation than the HO herdmates of the 3-breed crossbred cows. However, 23% of the first-lactation HO herdmates of the 2-breed crossbred cows were also the herdmates of the 3-breed crossbred cows.

Independent variables for the statistical analysis of 305-d milk (kg), fat (kg), and protein (kg) production; peak production (kg); DIM of peak production; and persistency of production for the first-lactation cows included the fixed effects of HYS and breed group of cow (MO × HO, VR × HO, MO × VR/HO, VR × MO/HO, or HO cows). Analysis of second and third lactations included the fixed effects of lactation number (2 or 3), HYS nested within lactation number, breed group of cow, interaction of lactation number and breed group, and the random effect of cow nested within breed group of cow.

The MIXED procedure of SAS 9.4 (SAS Institute Inc., Cary, NC) was used to conduct the ANOVA and to obtain least squares means and standard errors.

RESULTS AND DISCUSSION

Goodness of Fit for the Alternative RR Across Breed Groups

Results for the comparison of alternative RR functions for goodness of fit with test-day observations are in Table 1. For first lactation, Legendre polynomial RR had the lowest MSPE among all RR functions with 63.73 for milk, 0.23 for fat, and 0.07 for protein production. Furthermore, for first lactation, the Ali-Schaeffer RR also had a lower MSPE for milk, fat, and protein production than the Wilmink RR. The Legendre polynomial RR had the lowest AIC and BIC for fat and protein production; however, the Wilmink RR had the lowest AIC for only fluid milk production.

For second and third lactations, the Legendre polynomial RR had the lowest MSPE for milk (112.32), fat (0.45), and protein (0.11) production than the Wilmink RR (Table 1). In summary, the Legendre polynomial RR had the best goodness of fit for the lactation curves from the test-day observations of milk, fat, and protein production across all breed groups for first-lactation cows and second- and third-lactation cows. The Legendre polynomial RR had the lowest AIC and BIC for fluid milk and fat and protein production. The AIC and BIC penalize models that contain a large number of parameters. However, a lower MSPE indicated more precise predictions, and would be preferred to determine goodness of fit.

Two-Breed Crossbred Cows Compared with Their HO Herdmates

Lactation-Curve Characteristics Other than Persistency. The effect of HYS and breed group significantly ($P < 0.01$) explained variation for all of the lactation-curve characteristics of milk, fat, and protein production for both first-lactation and second- and third-lactation cows. Furthermore, the effect of lactation number and the interaction of breed group and lactation number also significantly ($P < 0.01$) explained variation for lactation-curve characteristics of milk, fat, and protein production for second and third lactations.

For fluid milk production of first-lactation cows, the MO × HO 2-breed crossbreds were not different ($P = 0.88$) from their HO herdmates for any of the lactation-curve characteristics. In contrast, the VR × HO 2-breed crossbreds had less ($P < 0.01$) fluid milk production compared with their HO herdmates in all 3 periods of first lactation, and this contributed to lower 305-d milk production

Table 1. Comparison of estimation functions from random regression for test-day observations of production based on mean square prediction error (MSPE) for the breed groups¹

Item and function	MSPE	AIC	BIC
First lactation			
Milk			
Wilmink	97.18	32,689	32,705
Ali-Schaeffer	78.98	136,014	136,046
Legendre polynomial	63.73	118,148	118,175
Fat			
Wilmink	0.29	8,658	8,673
Ali-Schaeffer	0.27	9,263	9,288
Legendre polynomial	0.23	8,295	8,315
Protein			
Wilmink	0.10	4,947	4,963
Ali-Schaeffer	0.08	4,764	4,784
Legendre polynomial	0.07	4,028	4,048
Second and third lactations			
Milk			
Wilmink	157.35	32,969	32,985
Ali-Schaeffer	133.30	123,360	123,391
Legendre polynomial	112.32	32,618	32,638
Fat			
Wilmink	0.56	10,417	10,433
Ali-Schaeffer	0.53	11,046	11,071
Legendre polynomial	0.45	10,250	10,270
Protein			
Wilmink	0.17	6,603	6,619
Ali-Schaeffer	0.13	6,662	6,672
Legendre polynomial	0.11	6,024	6,044

¹The bold values indicate the lowest MSPE (most desirable) among estimation functions for each production trait.

compared with their first-lactation HO herdmatres. Additionally, the VR × HO 2-breed crossbreds had 2 kg less ($P < 0.01$) peak milk production compared with their HO herdmatres. However, the VR × HO 2-breed crossbreds did not differ ($P = 0.63$) from their HO herdmatres for DIM of peak milk production. The results in this study for 305-d milk production of first-lactation cows agree with Hazel et al. (2017), who reported MO × HO 2-breed crossbred cows did not differ from their HO herdmatres for fluid milk production but VR × HO 2-breed crossbred cows had 4% less fluid milk production compared with their HO herdmatres during first lactation. Hazel et al. (2017) used similar data from the same 7 herds as this study; however, their study included cows that completed fewer than 250 DIM and were projected to 305 d using best prediction.

For fluid milk production of second and third lactations, the MO × HO 2-breed crossbreds did not differ ($P = 0.58$) from their HO herdmatres in any of the 3 periods of lactation and, therefore, did not differ for 305-d milk production (Table 2). The results for 305-d fluid milk production of the MO × HO 2-breed crossbreds compared with their second- and third-lactation HO herdmatres agreed with those of Hazel et al. (2014), who found the MO × HO 2-breed crossbred cows did not differ from their HO herdmatres for fluid milk production of second- and third-lactation cows in 2 institutional herds. Also, for second and third lactations, the VR × HO

2-breed crossbreds had less fluid milk production in all 3 periods of lactation and, therefore, had less 305-d milk production compared with their HO herdmatres (Table 2).

Historically, fluid milk production (kg) was the prevailing measure of productivity of cows. However, in recent years, production of fat and protein solids (kg) has become the most relevant measure of production revenue for most herds of cows. For first-lactation cows, the MO × HO 2-breed crossbreds had more ($P < 0.01$) fat production (kg) in the middle 102 DIM and final 100 DIM compared with their HO herdmatres (Table 3). More fat production (kg) of the MO × HO 2-breed crossbreds in the latter two-thirds of lactation contributed to more 305-d fat production compared with their HO herdmatres. Similarly, the VR × HO 2-breed crossbreds had significantly more fat production (kg) in the middle 102 DIM compared with their HO herdmatres. The advantage of more fat production (kg) for the VR × HO 2-breed crossbreds in the middle 102 DIM resulted in +5 kg more ($P < 0.05$) 305-d fat production compared with their first-lactation HO herdmatres (Table 3).

For second- and third-lactation cows, both the MO × HO and the VR × HO 2-breed crossbreds were not different ($P > 0.25$) from their HO herdmatres for fat production (kg) in the initial 100 DIM or final 100 DIM (Table 3). However, the MO × HO and VR × HO 2-breed crossbreds had +3 kg more ($P < 0.05$) fat production in the middle 102 d of lactation compared with their HO herdmatres.

Table 2. Least squares means of lactation-curve characteristics for milk production of 2-breed crossbred cows compared with their HO herdmates

Item	HO	MO × HO	VR × HO	SEM
First lactation				
n	1,073	524	548	
305-d milk (kg)	11,657	11,669	11,098**	45–65
Peak milk per day (kg)	43	43	41**	0.16–0.22
DIM of peak milk (d)	150	153	152	1.7–2.4
Initial 100 DIM (kg)	3,626	3,577	3,458**	15–21
Middle 102 DIM (kg)	4,246	4,268	4,051**	16–23
Final 100 DIM (kg)	3,785	3,823	3,589**	17–25
Second and third lactations				
n	1,223	650	633	
305-d milk (kg)	14,147	14,086	13,312**	69–95
Peak milk per day (kg)	55	55	52**	0.24–0.33
DIM of peak milk (d)	96	96	95	0.9–1.2
Initial 100 DIM (kg)	5,102	5,077	4,838**	24–33
Middle 102 DIM (kg)	5,141	5,142	4,850**	25–34
Final 100 DIM (kg)	3,909	3,867	3,629**	28–38

***P* < 0.01 for difference of crossbred from HO.

For first-lactation cows, the MO × HO 2-breed crossbreds had more (*P* < 0.01) protein production (kg) in all 3 periods of lactation compared with their HO herdmates (Table 3), and this resulted in more 305-d protein production with RR (+14 kg). Moreover, the VR × HO 2-breed crossbreds had significantly more protein production (kg) compared with their first-lactation HO herdmates in the middle 102 DIM and final 100 DIM, and this led to +4 kg more (*P* < 0.05) 305-d protein production. Additionally, the MO × HO 2-breed crossbreds had significantly more peak protein production compared with their HO herdmates (+0.06 kg). The VR × HO 2-breed crossbreds also had more (*P* < 0.05) peak protein production (+0.03 kg and +0.02 kg, respectively) compared with their HO herdmates.

For second and third lactations, the MO × HO 2-breed crossbreds also had more (*P* < 0.01) protein production (kg) in all 3 periods of lactation compared with their HO herdmates, and this resulted in the MO × HO 2-breed crossbreds having more (*P* < 0.01) 305-d protein production (kg) compared with their HO herdmates (Table 3). Furthermore, the MO × HO 2-breed crossbreds had significantly more peak protein production (kg) compared with their HO herdmates as well as more protein production (kg) throughout lactation compared with their HO herdmates. The VR × HO 2-breed crossbreds were not different (*P* = 0.62) from their second- and third-lactation HO herdmates for any of the lactation-curve characteristics for protein production.

Table 3. Least squares means of lactation-curve characteristics for fat and protein production of 2-breed crossbred cows compared with their HO herdmates

Item	Fat				Protein			
	HO	MO × HO	VR × HO	SEM	HO	MO × HO	VR × HO	SEM
First lactation								
n	1,073	524	548		1,073	524	548	
305-d production (kg)	431	440**	436*	1.6–2.2	351	365**	355*	1.2–2.0
Peak per day (kg)	1.53	1.57**	1.57**	0.005–0.008	1.27	1.33**	1.30*	0.004–0.007
DIM of peak (d)	178	183	178	2.1–3.0	189	194	190	1.7–2.4
Initial 100 DIM (kg)	135	136	136	0.6–0.8	106	108**	106	0.4–0.5
Middle 102 DIM (kg)	152	156**	155**	0.6–0.8	126	132**	128**	0.4–0.6
Final 100 DIM (kg)	144	148**	145	0.6–0.8	119	125**	121*	0.5–0.7
Second and third lactations								
n	1,223	650	633		1,223	650	633	
305-d production (kg)	501	507	501	2.8–4.3	428	445**	429	0.6–0.8
Peak per day (kg)	1.86	1.88	1.88	0.009–0.012	1.58	1.64**	1.59	0.006–0.008
DIM of peak (d)	81	83	89**	1.6–2.2	109	111	110	1.5–2.0
Initial 100 DIM (kg)	179	181	179	0.9–1.2	149	155**	149	0.6–0.8
Middle 102 DIM (kg)	176	179*	179*	0.9–1.2	153	160**	154	0.7–0.9
Final 100 DIM (kg)	146	147	144	0.9–1.3	126	130**	126	0.8–1.1

P* < 0.05 for difference of crossbreds from HO; *P* < 0.01 for difference of crossbred from HO.

Table 4. Least squares means of persistency¹ for milk, fat, and protein production of 2-breed crossbred cows compared with their HO herdmates

Item	HO	MO × HO	VR × HO
First lactation			
n	1,073	524	548
Milk (kg)	159.6	246.4**	130.5
Fat (kg)	8.8	11.0**	9.7
Protein (kg)	14.1	16.8**	15.2*
Second and third lactations			
n	1,223	650	633
Milk (kg)	-1,187.8	-1,208.4	-1,199.8
Fat (kg)	-33.6	-33.6	-34.6
Protein (kg)	-22.7	-25.4*	-23.5

¹Production in the final 100 DIM (206–305 d) minus production in the initial 100 DIM (4–103 d).

* $P < 0.05$ for difference of crossbreds from HO; ** $P < 0.01$ for difference of crossbred from HO.

The results for 305-d fat and protein production for first-lactation cows align with other research that compared MO × HO 2-breed crossbreds with their HO herdmates. Hazel et al. (2017) reported MO × HO 2-breed crossbred cows had 3% more fat plus protein production compared with their HO herdmates during first lactation. Malchiodi et al. (2014) reported 5% more fat production and equal protein production (kg) for MO × HO 2-breed crossbred cows compared with their HO herdmates during first lactation. The results in this study agree with Hazel et al. (2017), who reported VR × HO 2-breed crossbred cows were not different from their HO herdmates for 305-d first-lactation production of fat, protein, or fat plus protein production but had less 305-d fluid milk production. Blöttner et al. (2011) reported Brown Swiss × HO 2-breed crossbred cows had more milk production compared with their HO herdmates in the final 100 DIM. Like the MO breed, the Brown Swiss is an Alpine breed, and the results of Blöttner et al. (2011),

along with the results of this study, suggest crossbreds of an Alpine breed with HO have more production in later periods of lactation than HO cows.

Persistency of Production. The effects of HYS and breed group significantly ($P < 0.01$) explained variation for persistency of milk, fat, and protein production for the first-lactation 2-breed crossbreds compared with their HO herdmates. For second and third lactations, the effect of lactation number and HYS nested within lactation number significantly ($P < 0.01$) explained variation for persistency of milk, fat, and protein production.

For first-lactation cows, the MO × HO 2-breed crossbreds had more persistency of milk, fat, and protein production compared with their HO herdmates (Table 4). However, the VR × HO 2-breed crossbreds did not differ ($P = 0.17$) from their first-lactation HO herdmates for persistency of milk and fat production (Table 4), but the VR × HO 2-breed crossbreds had significantly more persistency of protein production compared with their HO herdmates.

For second and third lactations, the MO × HO 2-breed crossbreds did not differ ($P = 0.57$) from their HO herdmates for persistency of milk and fat production, but they had less ($P < 0.05$) persistency of protein production compared with their HO herdmates (Table 4). The VR × HO 2-breed crossbreds did not differ ($P > 0.40$) from their HO herdmates for persistency of milk, fat, and protein production (Table 4).

These results suggest the first-lactation MO × HO 2-breed crossbreds had more horizontal lactation curves compared with their first-lactation HO herdmates and had more fat and protein production after peak production compared with their HO herdmates. More persistency of production has been associated with numerous beneficial outcomes for dairy cows. Sölkner and Fuchs

Table 5. Least squares means of lactation-curve characteristics for milk production of 3-breed crossbred cows compared with their HO herdmates

Item	HO	MO × VR/HO	VR × MO/HO	SEM
First lactation				
n	1,043	479	430	
305-d milk (kg)	12,037	11,019**	10,754**	49–75
Peak milk per day (kg)	44	41**	40**	0.17–0.26
DIM of peak milk (d)	149	149	140**	1.5–2.3
Initial 100 DIM (kg)	3,745	3,349**	3,379**	16–25
Middle 102 DIM (kg)	4,397	4,115**	3,977**	17–26
Final 100 DIM (kg)	3,895	3,555**	3,398**	19–29
Second and third lactations				
n	827	431	399	
305-d milk (kg)	14,309	13,264**	12,860**	78–120
Peak milk per day (kg)	56	52**	52**	0.27–0.41
DIM of peak milk (d)	95	98	96	1.0–1.6
Initial 100 DIM (kg)	5,180	4,772**	4,756**	27–42
Middle 102 DIM (kg)	5,210	4,880**	4,787**	28–43
Final 100 DIM (kg)	3,924	3,613**	3,324**	32–49

** $P < 0.01$ for difference of crossbred from HO.

(1987) found cows with more persistency of production were more feed efficient compared with cows with less persistency of production. Muir et al. (2004) reported more persistency of production was positively correlated with higher conception at first insemination for first-lactation cows. Appuhamy et al. (2007) reported cows with more persistency of production had less incidence of mastitis and metabolic diseases compared with cows with less persistency of production. Therefore, the results for persistency of production in this study were not surprising, because crossbred cows of the MO, VR, and HO breeds were reported to have more feed efficiency (Shonka-Martin et al., 2019; Pereira et al., 2022), superior fertility (Heins et al., 2006; Heins and Hansen, 2012; Hazel et al., 2017), and lower health treatment costs (Hazel et al., 2020) compared with their HO herd mates. The advantages for persistency of production for the MO × HO 2-breed crossbreds in this study could potentially be explained by heterosis, but the advantages could also be explained by additive genetic effects from the 50% MO content of the 2-breed crossbreds.

Our results suggested the VR × HO 2-breed crossbreds were similar to their HO herd mates for persistency of production, and this agreed with a Canadian study of the lactation-curve characteristics of 2-breed crossbred cows of HO and Ayrshire that reported heterosis did not affect the shape of lactation curves for crossbreds of those 2 breeds (Batra, 1986). Furthermore, Heins et al. (2006) suggested that HO and crossbred cows sired by MO and Scandinavian Red bulls were similar for persistency of production throughout lactation, which is similar to results found in the current study.

Three-Breed Crossbred Cows Compared with Their HO Herd mates

Lactation-Curve Characteristics Other than Persistency. The effect of HYS significantly ($P < 0.01$) explained variation for all lactation-curve characteristics of the first-lactation 3-breed crossbreds compared with their HO herd mates, and breed group significantly explained variation for all lactation-curve characteristics except for DIM of peak production and for fluid milk production in the initial 100 DIM. For second and third lactations, the effects of lactation number, HYS nested within breed group, and breed group significantly ($P < 0.01$) explained variation for all lactation-curve characteristics.

For first-lactation cows, the MO × VR/HO 3-breed crossbreds had significantly less milk (Table 5), fat (Table 6), and protein (Table 6) production in the initial 100 DIM and the final 100 DIM compared with their HO herd mates. Consequently, the MO × VR/HO 3-breed crossbreds had significantly less 305-d milk, fat, and

Table 6. Least squares means of lactation-curve characteristics for fat and protein production of 3-breed crossbred cows compared with their HO herd mates

Item	Fat production					Protein production				
	HO	MO × VR/HO	VR × MO/HO	SEM		HO	MO × VR/HO	VR × MO/HO	SEM	
First lactation										
n	1,043	479	430			1,043	479	430		
305-d production (kg)	442	431**	420**	1.7-2.7		364	358**	350**	1.3-2.0	
Peak per day (kg)		1.58	1.52**	0.006-0.010			1.32	1.29**	0.005-0.007	
DIM of peak (d)	160	157	149**	1.9-2.8		183	172**	170**	1.6-2.4	
Initial 100 DIM (kg)	139	133**	132**	0.6-0.9		110	106**	106**	0.4-0.6	
Middle 102 DIM (kg)	156	157	152**	0.6-1.0		132	132	128**	0.5-0.7	
Final 100 DIM (kg)	147	141**	136**	0.6-1.0		123	120**	116**	0.6-0.8	
Second and third lactations										
n	827	431	399			827	431	399		
305-d production (kg)	509	494**	478**	2.8-4.3		432	435	420**	2.2-3.4	
Peak per day (kg)		1.83**	1.84**	0.009-0.015			1.62	1.61	0.007-0.011	
DIM of peak (d)	78	92**	83	1.8-2.8		106	106	105	1.7-2.6	
Initial 100 DIM (kg)	183	176**	174**	1.0-1.5		151	153	150	0.7-1.1	
Middle 102 DIM (kg)	179	176	173**	1.0-1.5		155	157	155	0.8-1.2	
Final 100 DIM (kg)	147	141**	131**	1.0-1.6		126	125	116**	1.0-1.5	

** $P < 0.01$ for difference of crossbreds from HO.

protein production compared with their HO herdmatres. However, the MO × VR/HO 3-breed crossbreds did not differ ($P = 0.36$) from their HO herdmatres for fat and protein production in the middle 102 DIM.

The MO × VR/HO 3-breed crossbreds had less ($P < 0.01$) peak milk production during first lactation compared with their HO herdmatres, but they were not different ($P = 0.89$) from their HO herdmatres for peak fat and protein production. The VR × MO/HO 3-breed crossbreds had less ($P < 0.01$) milk, fat, and protein production in all 3 periods of lactation and, therefore, had significantly less 305-d milk, fat, and protein production during first lactation compared with their HO herdmatres. Furthermore, the VR × MO/HO 3-breed crossbreds had significantly less peak milk, fat, and protein production compared with their HO herdmatres during first lactation.

For second and third lactations, the MO × VR/HO 3-breed crossbreds had significantly less milk (Table 5) and fat (Table 6) production in the initial 100 DIM and the final 100 DIM compared with their HO herdmatres, and this contributed to significantly less 305-d milk and fat production compared with their HO herdmatres. The MO × VR/HO 3-breed crossbreds had significantly less milk and fat production in the middle 102 DIM compared with their HO herdmatres, except the MO × VR/HO 3-breed crossbreds did not differ ($P = 0.15$) from their HO herdmatres for fat production in the middle 102 DIM. Furthermore, the MO × VR/HO 3-breed crossbreds in second and third lactations were not different ($P = 0.43$) from their HO herdmatres for protein production in all 3 periods of lactation and for 305-d protein production (Table 6). In contrast, the VR × MO/HO 3-breed crossbreds had significantly less milk (Table 5) and fat (Table 6) production in all 3 periods of lactation compared with their HO herdmatres. The VR × MO/HO 3-breed crossbreds in second and third lactations did not differ ($P > 0.26$) from their HO herdmatres for protein production

in the initial 100 DIM or the middle 102 DIM, but they had significantly less protein production compared with their HO herdmatres in the final 100 DIM (Table 6). The VR × MO/HO 3-breed crossbreds had significantly less 305-d milk (Table 5), fat (Table 6), and protein (Table 6) production compared with their HO herdmatres.

For both groups for lactation numbers of the MO × VR/HO 3-breed crossbreds were similar to their respective HO herdmatres for fat and protein production in the middle 102 DIM, whereas the VR × MO/HO 3-breed crossbreds had significantly less fat and protein production in the middle 102 DIM compared with their HO herdmatres. The difference between the MO × VR/HO and VR × MO/HO 3-breed crossbreds compared with their HO herdmatres for fat and protein production in the middle 102 DIM could potentially be explained by their mean difference for MO content.

Persistency of Production. For first-lactation cows, the effects of HYS and breed group significantly ($P < 0.01$) explained variation of persistency of milk, fat, and protein production. For second and third lactations, the effects of HYS nested within lactation and breed group significantly ($P < 0.01$) explained variation for persistency of milk, fat, and protein production.

The first-lactation MO × VR/HO 3-breed crossbreds had significantly ($P < 0.05$) more persistency of fluid milk production compared with their HO herdmatres, but they were not different ($P = 0.24$) from their HO herdmatres for persistency of fat and protein production. The VR × MO/HO 3-breed crossbreds had significantly less persistency of milk, fat, and protein production compared with their HO herdmatres (Table 7).

For second and third lactations, the MO × VR/HO 3-breed crossbreds had more ($P < 0.05$) persistency of fluid milk production compared with their HO herdmatres (Table 7). However, the MO × VR/HO 3-breed crossbreds did not differ ($P = 0.45$) from their HO herdmatres

Table 7. Least squares means of persistency¹ for milk, fat, and protein production of 3-breed crossbred cows compared with their HO herdmatres

Item	HO	MO × VR/HO	VR × MO/HO
First lactation			
n	1,043	479	430
Milk (kg)	150.5	206.1*	19.7**
Fat (kg)	7.5	7.3	3.5**
Protein (kg)	13.3	14.1	10.0**
Second and third lactations			
n	827	431	399
Milk (kg)	-1,252.9	-1,156.7*	-1,435.5**
Fat (kg)	-35.6	-34.4	-44.2**
Protein (kg)	-25.6	-27.5	-33.9**

¹Production in the final 100 DIM (206–305 d) minus production in the initial 100 DIM (4–103 d).

* $P < 0.05$ for difference of crossbreds from HO; ** $P < 0.01$ for difference of crossbred from HO.

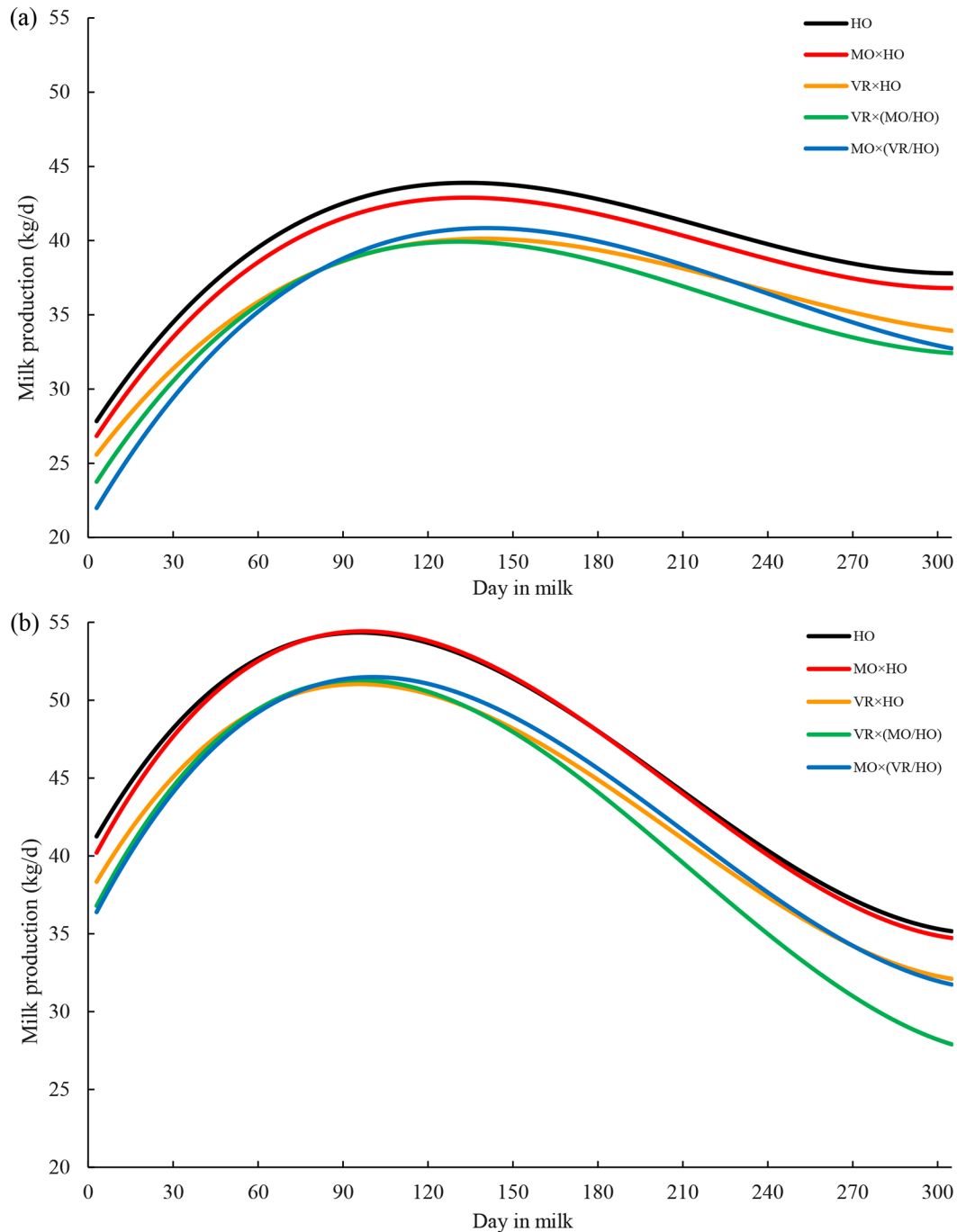


Figure 1. Lactation curves of (a) first lactation and (b) second and third lactations of purebred Holstein, 2-breed crossbred, and 3-breed crossbred cows for fluid milk production.

for persistency of fat production (Table 7). The MO × VR/HO 3-breed crossbreds did not differ ($P = 0.24$) from their HO herdmates for persistency of protein production. The VR × MO/HO 3-breed crossbreds had less ($P < 0.01$) persistency of milk, fat, and protein production compared with their HO herdmates.

Shape of Lactation Curves of Crossbred Cows Compared with Their HO Herdmates

Lactation curves of the 2-breed and 3-breed crossbred cows for daily milk production with Legendre polynomial RR for first-lactation cows and second and third

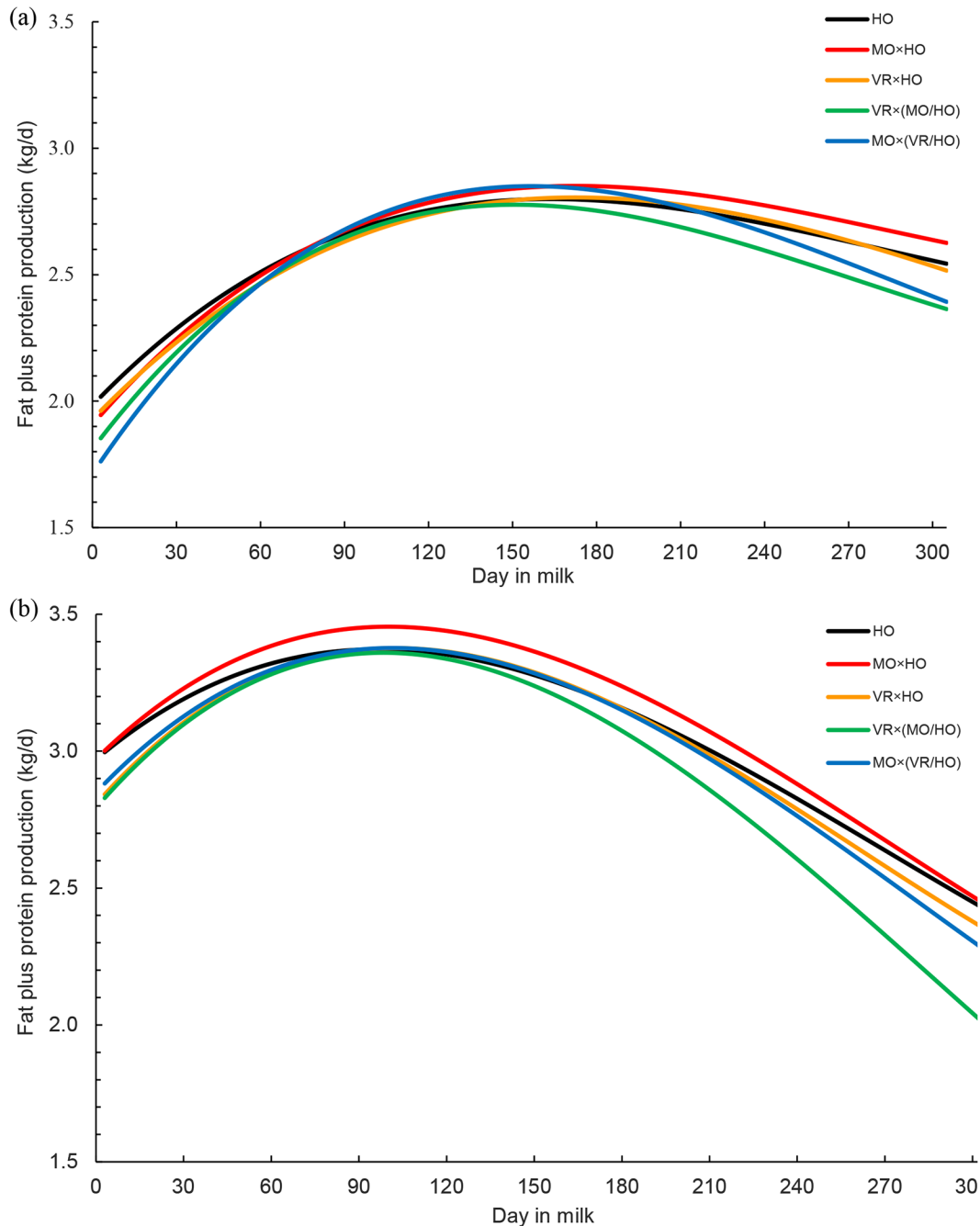


Figure 2. Lactation curves of (a) first lactation and (b) second and third lactations of purebred Holstein, 2-breed crossbred, and 3-breed crossbred cows for fat plus protein production.

lactation HO are in Figure 1. For first-lactation cows, the milk production curve was more horizontal than the milk production curve for second and third lactations. The milk production increased from d 1 after calving until 90 d postpartum for both lactation groups, and gradually decreased until the end of lactation (Figure 1). The lactation curves were different for all second- and third-lactation

HO and crossbred cows compared with first-lactation cows. The first-lactation cows had peak production with a longer plateau and a more gradual decline until the end of lactation (Figure 1).

Figure 2 has lactation curves of 2-breed and 3-breed crossbred cows for daily fat plus protein production with the Legendre polynomial RR for first-lactation cows and

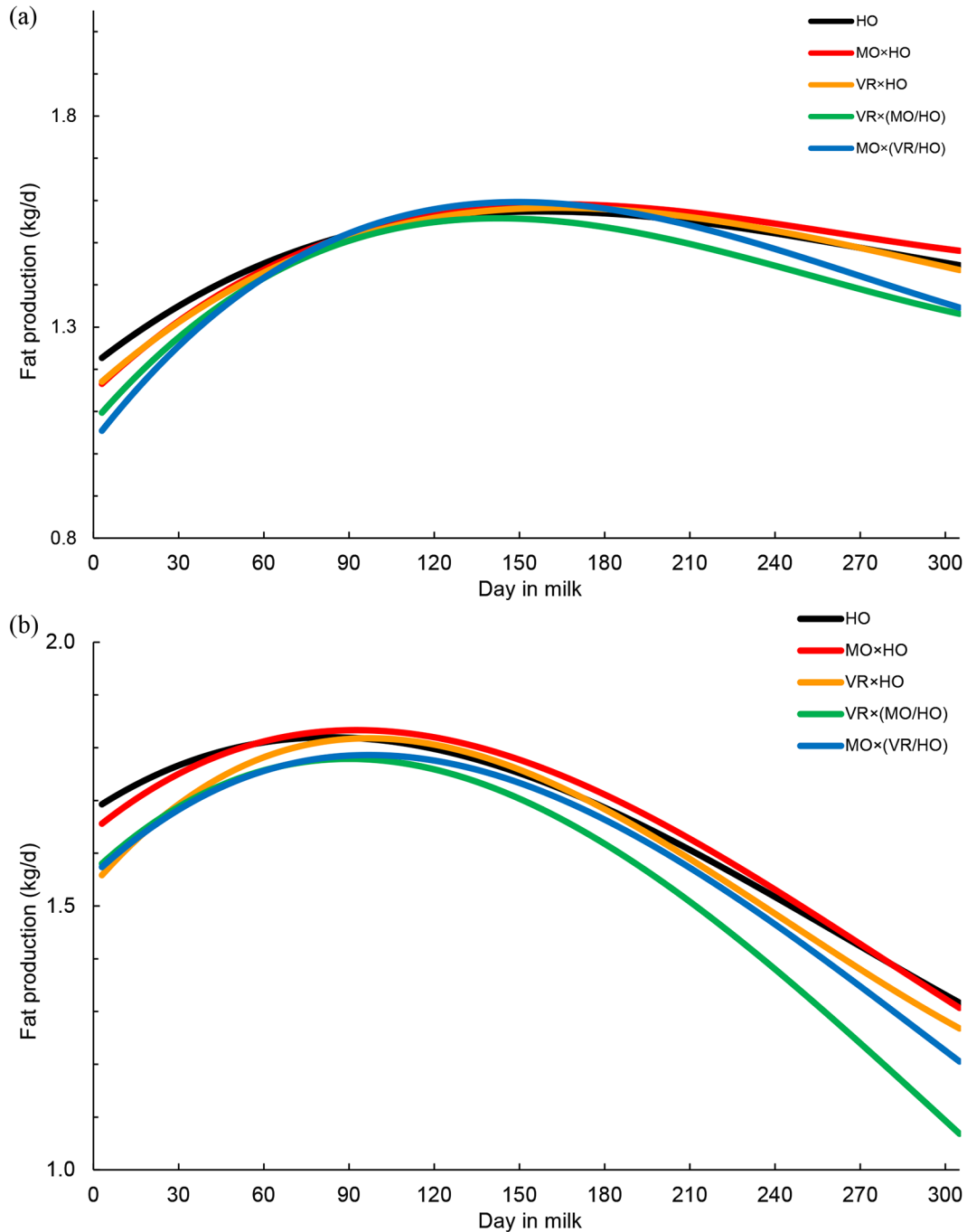


Figure 3. Lactation curves of (a) first lactation and (b) second and third lactations of purebred Holstein, 2-breed crossbred, and 3-breed crossbred cows for fat production.

second- and third-lactation HO cows. The fat plus protein production curve for first-lactation cows peaked at 150 DIM with a gradual decline until the end of lactation. However, for second and third lactations, daily fat plus protein production peaked at 90 DIM and had a steeper decline than for first-lactation cows until the end of lactation. Again, the MO × HO 2-breed crossbreds had higher

fat plus protein production compared with their HO herdmates. The results of the current study for lactation-curve characteristics are similar to those of Pipino et al. (2019), who reported crossbred cows had higher fat and protein production, but no difference for milk production compared with HO cows. Figure 3 has lactation curves of purebred HO, 2-breed crossbred, and 3-breed crossbred

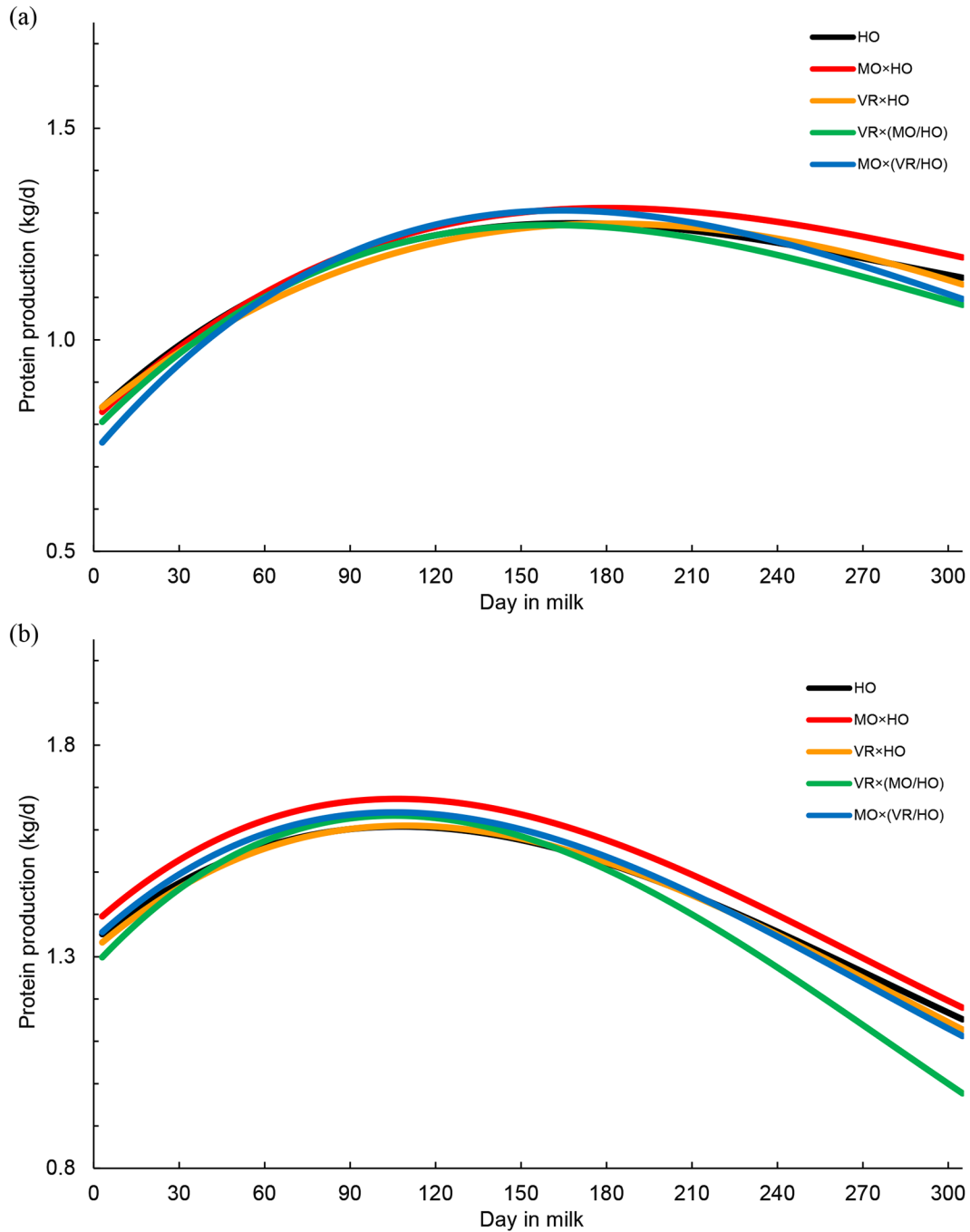


Figure 4. Lactation curves of (a) first lactation and (b) second and third lactations of purebred Holstein, 2-breed crossbred, and 3-breed crossbred cows for protein production.

cows for daily fat production, and Figure 4 has lactation curves of purebred HO, 2-breed crossbred, and 3-breed crossbred cows for daily protein production. For fat and protein production, first-lactation cows peaked around 150 DIM. However, for second and third lactations, fat and protein production peaked at 90 DIM with a steep decline until the end of lactation.

The production traits in this study were not adjusted for the fertility status of cows. If production had been adjusted for days open, the lessened persistency of production for the VR × MO/HO 3-breed crossbreds compared with their HO herdmates may have been less pronounced because pregnancy has a meaningful effect on production during later stages of gestation (Batra, 1986).

CONCLUSIONS

The RR has been used by most countries globally to estimate 305-d production for genetic evaluation but is not used for genetic evaluation in the United States. The MO × HO and VR × HO 2-breed crossbreds in this study had similar or more fat and protein production compared with their HO herdmates during 305-d lactations. However, the 2-breed crossbreds generally had more persistency of production compared with their HO herdmates, and more persistency of production is often preferred by dairy producers. This study considered only cows from the first 2 generations of a continuous 3-breed rotation for crossbreeding. However, the results suggest crossbred cows of the MO, VR, and HO breeds may have advantages over HO cows for persistency of production in high-performance herds.

NOTES

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Abbreviations used: AIC = Akaike's information criterion; BIC = Bayesian information criteria; HO = Holstein; HYS = herd-year-season; MO = Montbéliarde; MSPE = mean square prediction error; RR = random regression; TIM = test interval method; VR = Viking Red.

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