Daily Profit of 3-Breed Crossbreds Compared to Holsteins – Our Experience from a 10-Year Designed Study

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Take Home Messages

- Unlike previous research on crossbreeding of dairy cattle, this 10-year study had controlled and balanced enrolment of foundation cows, was carefully designed, used high-ranking artificial insemination (AI) bulls for all breeds, and had uniform data recording in high-production herds.
- The use of the Holstein, Viking Red, and Montbéliarde breeds in a 3-breed rotational program is marketed as ProCROSS©.
- Daily fat + protein production for lifetimes of cows was 1% higher for 2-breed crossbreds (Viking Red×Holstein and Montbéliarde×Holstein) and 1% lower for 3-breed crossbreds compared with their Holstein herdmates.
- All generations of the crossbred cows had lower stillbirth rates, and the 3-breed crossbred calves born to 2-breed crossbred dams had one-half the number of stillborn calves at 1st calving compared with their Holstein herdmates.
- The 2-breed crossbreds had 12 fewer days open and the 3-breed crossbreds had 17 fewer days open compared with their Holstein herdmates.
- Health treatment cost was 23% lower for the 2-breed crossbreds and 17% lower for 3-breed crossbreds compared with their Holstein herdmates.
- Lifetime death loss was 4% lower for both the 2-breed crossbreds and the 3-breed crossbreds compared with their Holstein herdmates.
- The combined 2-breed and 3-breed crossbreds had 153 more days in the herd compared with their Holstein herdmates. Therefore, replacement cost was substantially lower for both the 2-breed and 3-breed crossbreds compared with their Holstein herdmates.
- Daily profit was 13% higher for the 2-breed crossbreds and 9% higher for the 3-breed crossbreds compared with that of their Holstein herdmates.
- The average inbreeding coefficient of U.S. Holstein females born in 2020 surpassed 8.5%, and the rate of annual increase in average inbreeding currently exceeds 0.4%, which seems to be an unsustainable annual increase into the future.
- Hybrid vigour from crossbreeding is most influential for traits related to fertility, health, and survival, and it falls on top of genetic improvement within breeds.

Motivation for the Study

Interest in crossbreeding of dairy cattle continues to increase globally. Selection in the Holstein (HO) breed for milk production has been tremendously successful over the past 40 years. That success resulted in the HO breed becoming almost a monoculture for milk production globally at the start of the 21st century. However, the HO breed has also selected strongly for larger body size and more angularity of cows on top of the selection for production. All three of these traits **have genetic antagonism with** fertility, health, and survival of cows; therefore, the HO breed experienced a rapid decline in these functional traits. In recent years, selection emphasis for the HO breed has shifted more to these functional traits, but they have low genetic control and continue to be antagonistic with the continued selection for production.

The adoption and use of genomic selection in the U.S. over the past 12 years has substantially accelerated the annual increase of average inbreeding of HO females, mostly due to a dramatic reduction of generation interval (time between each generation). Therefore, the average inbreeding coefficient of U.S. Holsteins rose to 8.59% for females born during 2020. For reference, the inbreeding resulting from a bull mated to his own daughter averages 25% and the mating of first cousins results in inbreeding averaging 6.25%, which is the level of average inbreeding U.S. HO females surpassed in 2014. More concerning is the acceleration of average inbreeding in recent years because average inbreeding has increased about 0.40% in each of the past five years. Inbreeding depression silently steals profit from dairy producers because it is expressed mostly for traits that are not readily noticeable such as embryo loss, less disease resistance, and reduced survival.

Hybrid vigour from crossbreeding is expressed as an opposite effect of inbreeding depression. When parents of different breeds are mated to create a crossbred offspring, the two genes at the same location on the chromosomes cannot be identical from a common ancestor. Therefore, recessive genes of both major and minor consequence are not likely to be expressed with crossbreeding. Hybrid vigour has been embraced by the pig, beef, sheep, chicken, and turkey industries for more than 40 years.

Hybrid vigour does not replace genetic improvement within breeds, which increases the frequency of desirable genes. The support for, and the stewardship of, breeds with robust genetic improvement programs is critical for successful crossbreeding programs. Dairy producers should select three breeds of dairy cattle that are appropriate for their specific management systems and use the highest-ranking AI bulls from each of the three breeds.

This 10-year study compared cows from 3-breed rotational crossbreeding using the HO, Viking Red (VR), and Montbéliarde (MO) breeds with their pure HO herdmates. The study was initiated in 2008 and continued through 2017. This 3-breed crossbreeding program is referred to as ProCROSS© and is jointly marketed by two breeding companies (Viking Genetics and Coopex Montbéliarde). The VR breed is the result of combining the genetic improvement programs of the previously separate Swedish Red, Finnish Ayrshire, and Danish Red breeds.

▪ Design of the Study

Seven Minnesota herds were enrolled in the study in 2008, and the managers of the herds committed 3,550 HO virgin heifers and cows as the 'foundation' females. The herds were elite for production. At the end of the study in December 2017, the seven herds had average production of 13,587 kg milk, 512 kg fat, and 426 kg protein with an average herd size of 982 cows. All herds fed cows a total mixed ration, and lactating cows were housed in free-stall confinement barns.

This study is unique, because no previous study on crossbreeding with U.S. commercial dairy herds was carefully designed regarding matings across generations. Each of the seven herds in the study offered a minimum of 250 foundation HO females, which were assigned by researchers to be mated so their descendants across generations would be either HO or ProCROSS. The foundation females were paired and assigned to the two breed types based on their age (for heifers), lactation number (for cows), sire, and production level.

At least 150 foundation females were mated in each herd to HO AI bulls as were their descendants across generations. Also, at least 100 foundation HO females were mated in each herd to either VR or MO AI bulls (in equal number) to initiate a 3-breed rotational program in both directions. The 2-breed crossbred offspring of the foundation females were mated to the third breed to create 3-breed crossbreds. Finally, all 3-breed crossbreds were mated to HO AI bulls to keep the rotation moving forward. The two alternative rotations of breeds in each direction continued in successive generations in a designated order such as in Figure 1.

Some of the herds decided to enroll more than 250 HO foundation females in the study, and those herds chose which breed type the additional foundation females would be assigned. The enrolment by individual herds ranged from 250 to 785 foundation females, and 44% of these were mated to HO AI bulls and 56% were mated equally to VR and MO AI bulls. Female progeny were housed and managed together in the herds and treated the same in all ways including age at first breeding, health treatment, and culling.

Semen from proven AI bulls from the three breeds was used to breed heifers and cows in the study. Producers chose the bulls in consultation with two genetic advisors of Minnesota Select Sires Co-op, Inc. Semen from the VR and MO bulls was imported to the U.S. by Creative Genetics of California and ranked highly for the Nordic Total Merit index or the French ISU index, which are the national indices for the 2 breeds. Herd managers were asked to select proven HO AI bulls ranking among the top 10% for the U.S. Net Merit Index, and all of the HO AI bulls were marketed by Select Sires, Inc.

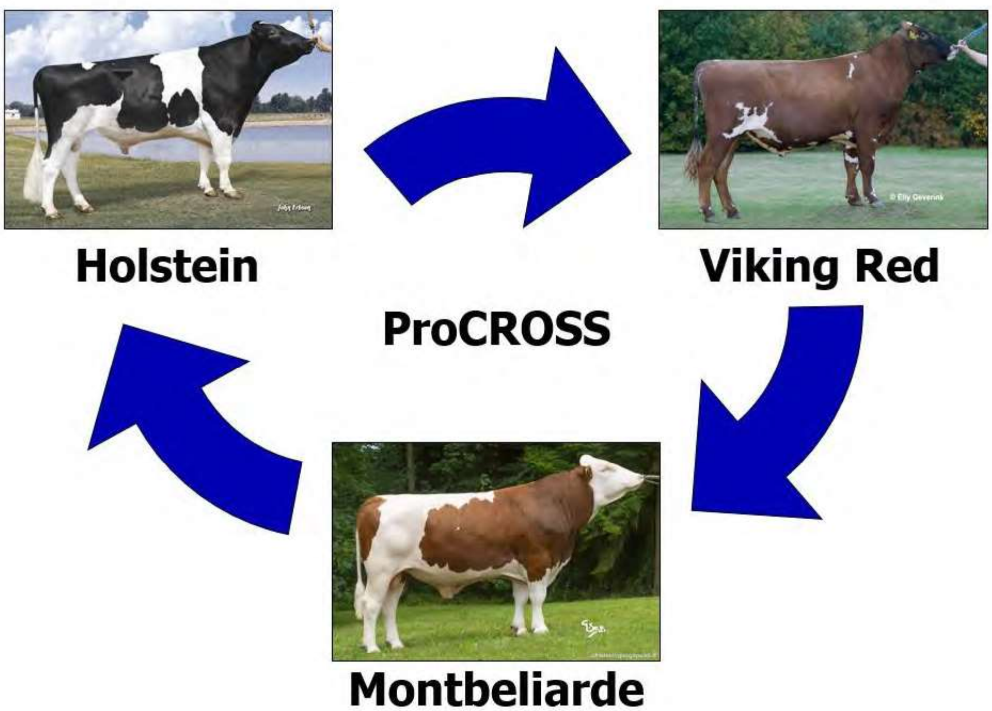

Figure 1. ProCROSS rotation initiated with Viking Red on Holstein female.

All heifers and cows were mated to individual AI bulls by the two genetic advisors with corrective mating for conformation. Furthermore, all matings of HO AI bulls with HO cows received inbreeding protection. The 2-breed crossbreds and their HO herdmates calved a first time starting in December 2010. The 3-breed crossbreds and their HO herdmates began calving in November 2012.

The window of time for each generation of cows in the study wasn't distinct and the generations overlapped, especially in the later years of the study. For example, some HO cows were herdmates with 2-breed as well as some 3-breed crossbreds. Observations were recorded until data collection ended on December 31, 2017. The experimental design, methods of analysis, and results of the study are provided in the scientific literature (Hazel, et al., 2020a,b; Hazel, et al., 2021).

▪ Analysis

Traits were analyzed within lactation number and also separately for the 2-breed crossbred and 3-breed generations and their HO herdmates. Cows that started lactation with an abortion (gestation length less than 260 days) were removed from the analysis of gestation length, stillbirth, fertility, production, and conformation, but they were included for the analysis of health treatment cost and survival. Also, cows sold for dairy purposes were excluded from the analysis of survival. Three seasons of calving were defined as January to April, May to August, and September to December for each herd. Cows that calved during seasons with fewer than three crossbred and three HO cows of the same generation and lactation number were removed from the analysis for a trait. Therefore, the number of cows analyzed varied somewhat from trait to trait. All traits were analyzed accounting for the effects of lactation number, herd-season of calving, and breed type of cow (such as VR×HO, MO×HO, and HO for the 1st generation).

Results are provided with probabilities that indicate whether reported differences are large enough to be statistically significant (can be taken seriously). The probability of $P < 0.10$ (symbolized with "†") indicates a difference with a 90% certainty of being real rather than due to chance. The probability of $P < 0.05$ (symbolized with "*") indicates a difference with a 95% certainty, and $P < 0.01$ (symbolized with "**") indicates a difference with a 99% certainty of being real rather than due to chance. The lack of a symbol indicates a difference may simply be due to chance.

▪ Results

Stillbirth

Stillbirth rates were numerically lower for all of the crossbred types at first calving and were significantly lower for both types of 2-breed crossbreds and about one-half lower for the VR×MO/HO 3-breed crossbreds compared with their HO herdmates (Table 1). Stillbirth rates were lower for cows at second and third calving regardless of breed type, and the differences were not statistically significant for the breed types.

Fertility

Both the VR×HO and MO×HO 2-breed crossbreds had significant advantages for fertility compared with their HO herdmates (Table 1). Averaged across lactations, the 2-breed crossbreds had 7.3% higher conception rate at first breeding compared with their HO herdmates, and the 2-breed crossbreds also had fewer times bred (–0.2 to –0.4) compared with their HO herdmates in first and second lactation. Days open averaged 134 days across the lactations for the HO herdmates, which is superior to the average of 145 days open of herds enrolled in U.S. dairy records management systems. However, the VR×HO 2-breed crossbreds averaged 8 fewer days open and the MO×HO 2-breed crossbreds averaged 17 fewer days open compared with their HO herdmates across lactations. Pregnancy rate was four percentage points higher for the 2-breed crossbreds compared with their HO herdmates across lactations.

Table 1. Fertility of VR×HO and MO×HO 2-breed crossbreds compared with their HO herdmates.

	Holstein		Difference from Holstein			
			VR×HO		MO×HO	
	Cows (n)	Average	Cows (n)	Difference	Cows (n)	Difference
First lactation						
Conception rate at first breeding	1,125	37%	558	+8%**	534	+6%*
Overall conception rate	1,127	37%	558	+4%*	534	+8%**
Times bred (up to five)	1,142	2.4	564	–.2*	541	–.3**
Days open	1,061	127	541	–7	517	–12**
Pregnancy rate	1,061	27%	541	+3%	517	+5%**
Second lactation						
Conception rate at first breeding	822	29%	425	+7%**	409	+11%**
Overall conception rate	824	31%	427	+4%*	410	+9%**
Times bred (up to five)	840	2.6	435	–.3**	424	–.4**
Days open	704	139	382	–11*	387	–22**
Pregnancy rate	704	24%	382	+3%*	387	+7%**
Third lactation						
Conception rate at first breeding	389	30%	251	+1%	253	+11%**
Overall conception rate	391	31%	252	+1%	255	+9%**
Times bred (up to five)	411	2.5	259	0	266	–.3*
Days open	336	143	231	–4	245	–23**
Pregnancy rate	336	23%	231	+1%	245	+7%**

* $P \leq 0.05$, ** $P \leq 0.01$ significantly different from Holstein.

The 3-breed crossbreds also were also superior for fertility compared with their HO herdmates for all fertility traits (Table 2). The HO herdmates had reasonable conception rate at first breeding (43% in first lactation and 35% for second and third lactation). Yet, the conception rate at first breeding was 8.7% higher for the 3-breed crossbreds averaged across lactations compared with their HO herdmates. Days open were more than two weeks fewer in first lactation, 2.5 weeks fewer in second lactation, and almost three weeks fewer in third lactation for the 3-breed crossbreds compared with their HO herdmates. The pregnancy rate superiority of the 3-breed crossbreds compared with their HO herdmates was +5% to +11%.

Concern about fertility is often the primary reason dairy producers consider crossbreeding. The superior fertility of the crossbreds may have mostly resulted from hybrid vigour. However, the outstanding performance of the 3-breed crossbreds compared with their HO herdmates is likely also because of the direct contributions of the VR and MO breeds, which have selected heavily for improved fertility for many years. Perhaps, more importantly, the VR and MO breeds haven't selected against body condition of cows. The relationship between less body condition and poor fertility of dairy cows is well established.

Table 2. Fertility of VR×MO/HO and MO×VR/HO 3-breed crossbreds compared with their HO herdmates.

	Holstein		Difference from Holstein			
			VR×MO/HO		MO×VR/HO	
	Cows (n)	Average	Cows (n)	Difference	Cows (n)	Difference
First lactation						
Conception rate at first breeding	1,124	43%	515	+9%**	458	+8%**
Overall conception rate	1,042	41%	491	+7%**	446	+9%**
Times bred (up to five)	1,033	2.2	491	–.3**	455	–.2**
Days open	1,022	126	471	–15**	433	–16**
Pregnancy rate	1,022	28%	471	+6%**	433	+7%**
Second lactation						
Conception rate at first breeding	612	35%	331	+7%†	292	+12%**
Overall conception rate	535	36%	301	+6%*	269	+8%**
Times bred (up to five)	566	2.4	306	–.2*	282	–.3**
Days open	512	134	283	–20**	263	–17**
Pregnancy rate	512	25%	283	+8%**	263	+6%**
Third lactation						
Conception rate at first breeding	250	35%	164	+7%	153	+13%*
Overall conception rate	215	33%	141	+11%**	132	+15%**
Times bred (up to five)	226	2.4	144	–.5**	142	–.5**
Days open	183	134	128	–15†	124	–25**
Pregnancy rate	183	25%	128	+5%†	124	+11%**

† $P \leq 0.10$, * $P \leq 0.05$, ** $P \leq 0.01$ significantly different from Holstein.

Health Treatment Cost

Health treatment cost of dairy cows is not well-documented in the U.S. because of the lack of complete and uniform recording. The seven herds in the study consistently recorded 16 types of health treatment events for the duration of the study. The veterinarians who provided service to the herds were interviewed, and they shared estimates of cost for medication and cost for veterinary care of specific types of treatment. Furthermore, the herd managers provided the estimated time required by their staff to restrain cows and to administer treatment. The time required for a treatment was converted to a labour cost for each of the 16 treatment types. The health treatment costs of a cow were assigned to each treatment event and added across lactation. This allowed multiple treatments of the same type for a cow within lactation. The cost of the 16 types of health treatment cost was added within each lactation of a cow, and this approach permitted a robust distribution of total health treatment costs for cows.

Health treatment cost for first lactation cows was low compared with the cost for second and third lactation cows for all breed types of cows (Table 3). The MO×HO 2-breed crossbreds had significantly lower total health treatment cost (–28%) compared with their HO herdmates during first lactation. The VR×HO 2-breed crossbreds had a tendency for lower total health treatment cost (–16%) compared with their HO herdmates during first lactation. Total health treatment cost during first lactation wasn't significantly different for the 3-breed crossbreds compared with their HO herdmates. In general, the seven herds had relatively low health treatment cost for all breed types during the first lactations of cows. However, differences between the breed types were noticeable in second and third lactation. Overall, the 2-breed crossbreds averaged 23% less total health treatment cost and the 3-breed crossbreds averaged 17% less total health treatment cost across their first three lactations compared with their pure HO herdmates.

Table 3. Total health treatment cost for 2-breed and 3-breed crossbreds compared with their HO herdmates.

	Holstein		Difference from Holstein			
			VR×HO		MO×HO	
Lactation number	Cows (n)	Average	Cows (n)	Difference	Cows (n)	Difference
First	1,280	$43	624	–$7†	592	–$12**
Second	1,007	$68	498	–$20**	471	–$21**
Third	577	$92	328	–$14**	334	–$25**

	Holstein		Difference from Holstein			
			VR×MO/HO		MO×VR/HO	
Lactation number	Cows (n)	Average	Cows (n)	Difference	Cows (n)	Difference
First	1,186	$43	537	–$3	502	–$5
Second	654	$81	333	–$15**	305	–$27**
Third	267	$109	158	–$18*	147	–$37**

† $P \leq 0.10$, * $P \leq 0.05$, ** $P \leq 0.01$ significantly different from Holstein.

Health treatment cost was broken down into five categories:

- mastitis (including mastitis diagnostic tests)
- lameness
- reproductive (retained placenta, metritis, cystic ovary, and other reproductive)
- metabolic (milk fever, displaced abomasum, ketosis, and digestive)
- miscellaneous (respiratory, injury, and all other).

Analysis of each health category indicated differences in total health treatment cost came mostly from three of the five categories — less mastitis, less metabolic, and less miscellaneous treatment cost — for both the 2-breed and 3-breed crossbreds compared with their HO herdmates.

Health treatment cost reported in this study was the economic cost for treatment of disease, but that cost may be a conservative reflection of the actual difference in disease status of the crossbreds compared with their HO herdmates. Recording of treatment events excluded subclinical disease that may have gone undetected, time for disease recovery, and time spent in a hospital pen. The gains from hybrid vigour for these sorts of health events, which are difficult to accurately record, were not captured. Furthermore, culling records from the herds revealed they often chose to cull or euthanize cows with diseases that had high treatment cost and cows with poor recovery prognosis.

Dairy breeding companies are now emphasizing health traits for genetic improvement of HO cows. However, slow progress is expected within a breed, because the genetic control of health is much less (heritability of 1% to 3%) than the genetic control of other traits such as production and conformation. The exploitation of hybrid vigour for improved cow health in addition to genetic improvement within breeds is expected to be more effective in achieving improved cow health than relying only on genetic improvement within a breed.

Survival

Despite the low average health treatment cost of first lactation HO cows in this study, significantly more of the VR×HO 2-breed and MO×HO 2-breed crossbreds calved a second time within 14 months and 17 months than did their HO herdmates (Table 4). The obvious explanation is the superiority of the 2-breed crossbreds for fertility compared with their HO herdmates in first lactation (Table 1). More VR×HO and MO×HO 2-breed crossbreds calved a third time within 14 months (+8% and +16%) and within 17 months after second calving (+6% and +12%) compared with their HO herdmates (Table 4).

Table 4. Survival of VR×HO and MO×HO 2-breed crossbreds compared with their HO herdmates.

	Holstein		Difference from Holstein			
			VR×HO		MO×HO	
	Cows (n)	Average	Cows (n)	Difference	Cows (n)	Difference
Virgin heifers						
Survival to first calving	1,581	86.7%	706	+3.0%†	695	+.2%
First lactation						
Second calving within 14 months	1,250	63%	608	+6%*	582	+8%**
Second calving within 17 months	1,239	76%	604	+5%*	576	+6%**
Death loss	1,223	4%	593	–1%	568	–1%
Second lactation						
Third calving within 14 months	983	46%	496	+8%**	470	+16%**
Third calving within 17 months	980	61%	496	+6%†	470	+12%**
Death loss	959	8%	483	–4%**	451	–2%
Third lactation						
Fourth calving within 14 months	559	40%	322	+9%*	329	+19%**
Fourth calving within 17 months	549	51%	322	+6%	328	+18%**
Death loss	560	8%	319	0%	330	–3%
Survival to subsequent calving						
Survival to second calving	1,223	81%	593	+4%†	568	+4%†
Survival to third calving	1,201	51%	581	+7%*	551	+12%**
Survival to fourth calving	1,012	27%	550	+5%†	516	+16%**
Died up to 45 months (after first calving)	640	16.3%	376	–5.1%**	358	–2.6%
Lived to at least 45 months (after first calving)	640	18.0%	376	+6.7%**	358	+15.2%**

† $P \leq 0.10$, * $P \leq 0.05$, ** $P \leq 0.01$ significantly different from Holstein.

The percentage of cows that calved again within 14 and 17 months measured both the time required for cows to calve again as well as whether they actually calved again. Few cows required longer than 17 months to calve again, because the herds in the study culled aggressively for both fertility and persistency of production in later lactation.

Actual survival to next calving is also in Table 4, and cows were required to calve a first time in order to be included. For the 2-breed crossbreds, 58% of the VR×HO and 63% of the MO×HO calved a third time, but only 51% of their HO herdmates calved a third time. Survival to fourth calving was even more different for the 2-breed crossbreds compared with their HO herdmates, because 32% of the VR×HO, 43% of the MO×HO, and 27% of the HO calved a fourth time.

Death loss within lactation was the number of cows that died divided by the number of cows that calved in that lactation (Table 4). Death loss was low during first lactation for all breed types. However, during second lactation, the VR×HO 2-breed crossbreds had 4% death loss compared with 8% death loss of their HO herdmates. Death loss was also compared up to 45 months after first calving. The HO herdmates of the crossbreds had 16.3% death loss, which is similar to the 15% to 16% death loss of HO cows born in 2008 to 2012 that are used for U.S. genetic evaluation. However, the VR×HO 2-breed crossbreds had significantly less death loss (11.2%) compared with their HO herdmates.

Table 5. Survival for VR×MO/HO and MO×VR/HO 3-breed crossbreds compared with their HO herdmates.

	Holstein		Difference from Holstein			
			VR×MO/HO		MO×VR/HO	
	Cows (n)	Average	Cows (n)	Difference	Cows (n)	Difference
Virgin heifers						
Survival to 1st calving	1,557	85.7%	667	+3.9%*	613	+3.1%
First lactation						
Second calving within 14 months	1,103	63%	506	+9%**	474	+6%†
Second calving within 17 months	1,018	76%	475	+5%	447	+1%
Death loss	1,057	4%	490	–2%	456	+1%
Second lactation						
Third calving within 14 months	586	48%	297	+16%**	275	+19%**
Third calving within 17 months	545	61%	273	+14%**	252	+13%**
Death loss	569	7%	293	–4%**	269	–3%
Third lactation						
Fourth calving within 14 months	202	37%	129	+29%**	115	+23%**
Fourth calving within 17 months	165	44%	97	+25%**	97	+21%**
Death loss	181	6%	111	–1%	103	–3%
Survival to subsequent calving						
Survival to second calving	1,057	84%	490	+4%*	456	–1%
Survival to third calving	681	51%	318	+14%**	309	+8%*
Survival to fourth calving	311	22%	124	+24%**	135	+15%**
Died up to 45 months (after first calving)	250	12.4%	109	–6.0%†	117	–3.0%
Lived to at least 45 months (after first calving)	250	17.6%	109	+13.6%**	117	+8.9%*

† $P \leq 0.10$, * $P \leq 0.05$, ** $P \leq 0.01$ significantly different from Holstein.

The VR×MO/HO 3-breed crossbreds (89.6%) and the MO×VR/HO 3-breed crossbreds (88.8%) had significantly higher survival rates compared with their HO herdmates (85.7%) from two days of age to first calving (Table 5). More of the 3-breed crossbreds (+6% and +9%) had a second calving within 14 months compared with the 63% survival rate of their HO herdmates (Table 5). For cows that calved a second time, significantly more 3-breed crossbreds calved a third time, and the difference for survival rate was 16% to 19% higher by 14 months after calving and 13% to 14% by 17 months after first calving compared to that of their HO herdmates. Differences between the breed types grew even larger for cows that calved a fourth time within 14 months of third calving because the VR×MO/HO (66%) and MO×VR/HO (60%) 3-breed crossbreds had a significantly higher survival rate compared with their HO herdmates (37%).

For the 3-breed crossbreds, death loss within each of the lactations was about one-half that of their HO herdmates. The 3% death loss of the VR×MO/HO crossbreds in second lactation was significantly lower than the 7% death loss of their HO herdmates. Up to 45 months after first calving, 6.4% of the VR×MO/HO and 9.4% of the MO×VR/HO 3-breed crossbreds died, but 12.4% of their HO herdmates died (Table 5).

The percentage of cows that survived to at least 45 months after first calving was 29% for the 2-breed crossbreds and 3-breed ProCROSS combined. On the other hand, only 18% of their HO herdmates survived to at least 45 months after first calving. Replacement cost is among the top three expenses for most herds.

Production

Actual (not mature equivalent) 305-day production was estimated from test-day records of milk, fat, and protein. Cows were required to have at least two test days to be included in the analysis. Cows that were milked longer than 305 days in lactation were limited to 305 days of production. Cows that became pregnant quickly after calving, which resulted in lactations less than 305 days, and cows that left the herd prior to 305 days in milk had their lactations projected to 305 days.

Lifetime production of a cow was actual daily production added across all days she was in the herd. Production from lactations longer than 305 days were included, and lactations of cows that were less than 305 days were not projected to 305 days for lifetime production. Cows that did not survive to a first test day were assigned 11.3 kg of milk, 0.397 kg of fat, and 0.340 kg of protein production for each day between calving and removal from the herd.

For lifetime production, 315 cows (23%) of the first-generation cows lived beyond 45 months in the herd or were still in the herd at the end of the study. For second generation cows, 100 cows (21%) lived beyond 45 months. For these cows, additional daily production was projected by multiplying the production per day up to 45 months after first calving by the predicted number of additional days that the cow remained in the herd. The projected production of each cow after 45 months was added to the production during their initial 45 months in the herd. Daily production for each cow was her lifetime production divided by the number of days she was in the herd (or her projected days in the herd) including the dry period. All the herds routinely milked most of their cows three times daily.

The herds had a young average age at first calving compared with the U.S. average. Age at calving was not significantly different for the 2-breed crossbreds compared with their HO herdmates for both first and second lactation (Table 6), and the MO×HO 2-breed crossbreds had a tendency to calve one-half month earlier compared with their HO herdmates in third lactation.

The fat + protein production of the MO×HO 2-breed crossbreds was 3% higher compared with that of their HO herdmates in first and second lactation. Furthermore, the VR×HO 2-breed crossbreds were not significantly different from their HO herdmates for fat + protein production in any of the lactations. For fluid milk volume, the VR×HO 2-breed crossbreds were significantly lower compared with their HO herdmates, but the MO×HO 2-breed crossbreds were not significantly different from their HO herdmates. The majority of dairy herds in the world are paid for the fat and protein solids in milk rather than the volume of fluid that carries the solids. Cows with extra fluid carrier (water) are often considered to be less desirable because more expense is needed to cool and ship the additional fluid carrier. Therefore, most dairy producers believe less fluid volume with higher percentages of solids is advantageous.

On a lifetime basis, both the VR×HO 2-breed crossbreds (+96 days) and the MO×HO 2-breed crossbreds (+219 days) had significantly more longevity (days) in the herd compared with their HO herdmates. The differences for days are equivalent to +3.2 months for the VR×HO 2-breed crossbreds and +7.2 months for the MO×HO 2-breed crossbreds compared with their HO herdmates. The additional length of time in the herd resulted in significantly more lifetime fat + protein production for the MO×HO 2-breed crossbreds compared with their HO herdmates (Table 6). For daily fat + protein production across the lifetimes of cows, the VR×HO 2-breed crossbreds had 1% less and the MO×HO 2-breed crossbreds had 2% more daily fat + protein production compared with their HO herdmates.

The 3-breed crossbreds had significantly younger age at calving for first, second, and third lactation compared with their HO herdmates (Table 7). On average, the 3-breed crossbreds calved 12 days sooner for first lactation, 21 days sooner for second lactation, and 49 days sooner for third lactation compared with their HO herdmates. The explanation for their younger ages at calving was their advantage for fertility compared with their HO herdmates (Table 2).

The VR×MO/HO and MO×VR/HO 3-breed crossbreds had significantly lower fat + protein solids production during first (–4%), second (–3%), and third (–4%) lactation compared with their HO herdmates (Table 7). The lower 305-day production was not surprising for two reasons: 1) the 305-day production wasn't adjusted for the fewer days open (their advantage for fertility) of the 3-breed crossbreds compared with their HO herdmates, and fewer days open lowers production of cows in the final trimester of pregnancy, and 2) the 3-breed crossbreds had an average HO content of only 25%.

Table 6. Production (actual, not mature equivalent) for 305-day lactations, for lifetime, and per day for the 2-breed crossbreds compared with their HO herdmates.

		Difference from Holstein	
	Holstein	VR×HO	MO×HO
First lactation			
Cows (number)	1,180	582	556
Age at calving (months)	23.8	0	0
305-day fat + protein (kg)	765	+11	+23**
305-day milk (kg)	11,378	–419**	+67
Second lactation			
Cows (number)	883	461	443
Age at calving (months)	36.5	–.1	–.1
305-day fat + protein (kg)	887	–5	+19**
305-day milk (kg)	13,338	–790**	–3
Third lactation			
Cows (number)	451	281	297
Age at calving (months)	48.9	–.4	–.5†
305-day fat + protein (kg)	927	0	+13
305-day milk (kg)	13,932	–665**	–72
Lifetime			
Cows (number)	640	376	358
Days in the herd	886	+96*	+219**
Fat + protein production (kg)	2,201	+196	+609**
Daily across lifetime			
Cows (number)	640	376	358
Fat + protein production (kg)	2.51	–.02**	+.06**

† $P \le 0.10$, * $P \le 0.05$, ** $P \le 0.01$ significantly different from Holstein.

On a lifetime basis, both the VR×MO/HO (+5.8 months) and MO×VR/HO (+3.8 months) 3-breed crossbreds had numerically more longevity compared with their HO herdmates, although the advantage of the MO×VR/HO crossbreds was not statistically significant. Because of their longer lives, both types of 3-breed crossbreds had numerically higher lifetime fat + protein production. For daily production of fat + protein production across their lifetimes, the VR×MO/HO 3-breed crossbreds were 2% lower and the MO×VR/HO 3-breed crossbreds were 1% higher compared with their HO herdmates.

ProCROSS© is a long-term and continuous rotational breeding program, and dairy producers must focus on the combined impact across generations of the rotation. When the daily fat + protein production of the VR×HO and MO×HO 2-breed crossbreds (–1% and +2%, respectively) and of the VR×MO/HO and

MO×VR/HO 3-breed crossbreds (–2% and +1%, respectively) are combined, the difference for daily fat + protein production from their HO herdmates was zero.

The daily fat + protein production of cows across their lifetimes is a more appropriate measure than 305-day production for comparing the differences between breed types. Daily fat + protein production includes the days that cows are dry. On average, the crossbreds in this study had more dry days compared with their HO herdmates because they calved more times during their lifetimes. However, calving more frequently also resulted in the crossbreds having more days during their lifetimes with peak production compared with their HO herdmates. If only lactating days of cows had been analyzed, the daily fat + protein production of the crossbreds would have been higher compared with their HO herdmates.

Table 7. Production (actual, not mature equivalent) for 305-day lactations, for lifetime, and per day for the 3-breed crossbreds compared with their HO herdmates.

		Difference from Holstein	
	Holstein	VR×MO/HO	MO×VR/HO
First lactation			
Cows (number)	1,073	505	462
Age at calving (months)	23.2	–.5**	–.3*
305-day fat + protein (kg)	795	–38**	–22**
305-day milk (kg)	11,803	–1,202**	–932**
Second lactation			
Cows (number)	582	309	291
Age at calving (months)	35.9	–.9**	–.6**
305-day fat + protein (kg)	906	–44**	–16†
305-day milk (kg)	13,551	–1,326**	–850**
Third lactation			
Cows (number)	228	143	134
Age at calving (months)	48.5	–1.7**	–1.6**
305-day fat + protein (kg)	953	–56**	–27*
305-day milk (kg)	14,295	–1,466**	–1,087**
Lifetime			
Cows (number)	250	109	117
Days in the herd	850	+176*	+117
Fat + protein production (kg)	2,132	+385†	+307
Daily across lifetime			
Cows (number)	250	109	117
Fat + protein production (kg)	2.55	–.06**	+.03**

† $P \leq 0.10$, * $P \leq 0.05$, ** $P \leq 0.01$

Conformation and Body Condition Score

Conformation had a scale of one to nine, and cows were evaluated once each lactation between two and 150 days after calving (average of 35 days) by the two genetic advisors of Minnesota Select Sires Co-op, Inc. Cows were evaluated every lactation, and this approach is unique for cows as they aged, because cows aren't routinely evaluated for conformation after first lactation by U.S. breed associations.

Stature

Stature had a scale of 1 = shorter to 9 = taller. The HO herdmates to the crossbreds increased in stature during first lactation (from 5.4 to 5.7). This result confirmed the HO herdmates of crossbred cows in this study became taller with time, despite an effort by dairy producers to select for shorter stature of their HO cows. Both the VR×HO 2-breed (4.0) and MO×HO 2-breed (4.7) crossbreds were significantly shorter for stature compared with their HO herdmates (5.4) in first lactation. This trend continued for second and third lactations. The 3-breed crossbreds were also shorter in stature compared with their HO herdmates for all lactations. Furthermore, the VR×MO/HO 3-breed (4.3) and MO×VR/HO 3-breed (4.5) crossbreds were both intermediate for stature between the extremes of their 2-breed dams.

Angularity and Body Condition Score (BCS)

The scale for angularity was 1 = round to 9 = angular. Body condition score had a scale from 1 = thin to 5 = obese. As expected, angularity and BCS had a strong relationship. All breed types of cows became more angular (less BCS) with age. Also, both generations of crossbreds had less angularity and more BCS compared with their HO herdmates. The MO×HO 2-breed (2.6) and MO×VR/HO 3-breed (2.6) crossbreds had the least angularity and MO×VR/HO 3-breed crossbreds had the highest BCS (3.90) for all breed types in first lactation. The relationship of lower BCS and reduced fertility, health, and survival of dairy cows is well documented.

Body Depth

Body depth had a scale of 1 = shallow to 9 = deep. All the 2-breed and 3-breed crossbreds had significantly shallower body depth than their HO herdmates. Cows with more body depth are more prone to displaced abomasum after calving because the digestive tract has more space to move after the calf is born. Therefore, less body depth of the crossbreds compared with their HO herdmates may have contributed to the lower incidence of metabolic treatment cost of the crossbreds compared with their HO herdmates in this study.

Foot Angle

The scale for foot angle was 1 = low to 9 = steep. The VR×HO 2-breed crossbreds had significantly lower foot angle compared with their HO herdmates, but only in second lactation (5.1 versus 5.6) and third lactation (4.9 versus 5.3). However, the MO×HO 2-breed crossbreds had significantly steeper foot angle compared with their HO herdmates in all lactations. Likewise, the MO×VR/HO 3-breed crossbreds had steeper foot angle compared with their HO herdmates. The VR×MO/HO 3-breed crossbreds had 0.5 steeper foot angle compared with their HO herdmates during first lactation, probably due to an average MO content of 25%.

Udder Clearance

Udder clearance had a scale of 1 = low to 9 = high and was evaluated as distance of the udder floor from the hock and not as distance from the ground. Therefore, cows with shorter stature (and shorter legs) had a disadvantage for udder clearance compared with their HO herdmates that had longer legs on average. In other words, udders with identical dimension received a lower score for cows with shorter stature. All the 2-breed and 3-breed crossbreds had less udder clearance compared with their HO herdmates.

Rear Teat Width

The scale for rear teat width was 1 = wide to 9 = close. In first lactation, the 2-breed (5.6) and 3-breed (5.4) crossbreds averaged more width between the rear teats and had scores closer to the midpoint of 5 compared with their HO herdmates (6.6). Also, the rear teat width became closer across the years of the study for their HO herdmates in first lactation (6.5 to 6.7 to 6.8). In second and third lactation, the 2-breed and 3-breed crossbreds also had more width between the rear teats compared with their HO herdmates.

Dairy producers express frustration with rear teats of cows that are close (touch or cross), especially for robotic milking. Significantly fewer 2-breed crossbreds in this study had touching or crossing rear teats compared with their HO herdmates in first lactation (5% versus 13%), second lactation (17% versus 28%), and third lactation (17% versus 29%).

Teat Length

Teat length had a scale of 1 = short to 9 = long. The VR×HO 2-breed crossbreds were not different for teat length from their HO herdmates. However, the MO×HO 2-breed crossbreds had significantly longer teats compared with their HO herdmates in second lactation (+0.7) and third lactation (+0.4). The 3-breed MO×VR/HO crossbreds had slightly longer (+0.4 and +0.5) teat length on average compared with their HO herdmates in first and second lactation. Extremely short teats are a functional problem for cows.

Lifetime Profit and Daily Profit

To be included in the analysis of lifetime profit and daily profit, cows were required to have the opportunity (based on the cut-off of data at the end of the study) to survive to 45 months in the herd. Also, at least 20 cows were required for each breed type of either 2-breed crossbreds or 3-breed crossbreds and their HO herdmates. This requirement permitted a fair comparison of breed types for lifetime performance by eliminating comparisons that included a small number of cows within herd. Therefore, cows from only three of the seven herds were compared for lifetime performance.

Lifetime profit was estimated from the income and expense accumulated by each cow on a daily basis and added across all days in the herd after first calving (Table 8). The income from production came from daily production of milk, fat, protein, and other solids, as well as income or loss from SCS, with the cost of hauling and milk marketing subtracted for each cow. The production prices were from the U.S. Federal Milk Marketing Order for the Upper Midwest for 2013 to 2017. Average component prices used were US$4.9650 per kg of fat, US$5.8631 per kg of protein, and US$0.6177 per kg of other solids.

Table 8. Income and expense to determine lifetime profit

	Value	Unit	Reference
Income (US$)			
Milk price	$38.01	100 kg	USDA FMMA 30[1]
Live female calf	$200	Calf	Lifetime Net Merit
Live male calf			
Holstein	$100	Calf	Heins et al. (2012)
Crossbred	$130	Calf	Study herds
Cull value during first lactation			
Holstein	$876	Cow	Study herds
VR-sired crossbred	$876	Cow	Study herds
MO-sired crossbred	$1,033	Cow	Study herds
Cull value during second and later lactation			
Holstein	$941	Cow	Study herds
VR-sired crossbred	$1,049	Cow	Study herds
MO-sired crossbred	$1,047	Cow	Study herds
Expense (US$)			
Feed (during lactation)	$0.2341	kg of DM	FINBIN[2]
Lactation overhead	$4.76	Day	FINBIN[2]
Replacement[3]	$1,910	Cow	Tranel (2019)
Dry cow overhead (including feed)	$3.50	Day	FINBIN[2]
Breeding	$27	Event	Study herds
Fertility hormones	$18	Event	Study herds
Palpation	$7	Event	Study herds
Hoof trimming	$15	Event	Study herds
Carcass disposal	$34	Cow	Study herds

[1] Upper Midwest average for 2013 to 2017
[2] Average for 2013-2017, Center for Farm Financial Management, University of Minnesota
[3] Replacement expense varied based on age at first calving for each cow

Lifetime profit was projected for all cows that lived beyond 45 months in the herd by multiplying each cow's daily profit up to 45 months by the predicted number of additional days the cow remained in the herd based on the survival rates of cows in each herd. However, cows that were projected beyond 45 months did not receive additional income from cull value and were not assessed additional expense for replacement or carcass disposal.

Daily profit of a cow was lifetime profit divided by the number of days in the herd. The most appropriate measure of profitability of cows on an ongoing basis within a herd is the daily profit per unit of available stall, cubicle, or pasture space. The daily income from production was 1% lower for VR×HO 2-breed crossbreds and 2% higher for MO×HO 2-breed crossbreds compared with their HO herdmates (Table 9), and this difference agreed well with the difference of the 2-breed crossbreds compared with their HO herdmates for daily fat + protein production. The calf value averaged US$0.07 more per cow per day for the 2-breed crossbreds compared with their HO herdmates (Table 9). The 2-breed crossbred cows had a 17% greater daily calf value compared with their HO herdmates because 1) crossbred male calves, particularly those with white faces from the MO breed, had a +US$30 higher sale price than HO calves, 2) crossbred cows had fewer stillborn calves than their HO herdmates, and 3) the crossbred cows calved more times during their lifetimes compared with their HO herdmates.

Table 9. Daily income and expense that contributed to daily profit for VR×HO and MO×HO 2-breed crossbreds compared with their HO herdmates.

	Holstein	Difference from Holstein	
		VR×HO	MO×HO
Cows (number)	640	376	358
Income (US$)			
Production	$14.82	–$.20**	+$.31**
Calf value	$.42	+$.06**	+$.07**
Cull value	$.69	+$.04**	–$.03**
Total income (US$)	$15.92	–$.09**	+$.36**
Percentage difference from Holstein		–1%	+2%
Expense (US$)			
Feed (during lactation)	$5.33	–$.11**	+$.02**
Lactation overhead	$4.19	–$.05**	–$.03**
Replacement	$1.59	–$.13**	–$.27**
Dry cow overhead (including feed)	$.42	+$.03**	+$.02**
Health treatment	$.24	–$.08**	–$.06**
Breeding	$.19	–$.01**	–$.02**
Total expense (US$)	$12.19	–$.33**	–$.36**
Percentage difference from Holstein		–3%	–3%

** $P \leq 0.01$ significantly different from Holstein.

The average cull value for VR×HO 2-breed crossbreds (US$908) and MO×HO 2-breed crossbreds (US$906) was significantly higher compared with that of their HO herdmates (US$785). However, these differences were not obvious when the cull value was divided by days in the herd to obtain daily cull value (Table 9), because the crossbreds averaged 158 more days in the herd compared with their HO herdmates. The total of production income, calf value, and cull value resulted in a daily total income of US$16.05 for the combined 2-breed crossbreds, which was 1% higher compared with US$15.92 for their HO herdmates.

Expense for feed while cows were lactating was the single largest expense for cows in the study. Individual feed intake was not available for cows. Therefore, feed intake was predicted from the formulas of the National Research Council. Feed intake was independently assigned for each cow on each day and depended on the week of lactation, on daily fat-corrected milk, and on body weight of cows. Body weight was not available for cows in the study, so body weight was set to 567 kg for all first lactation cows and 680 kg for all second and later lactation cows regardless of breed type to estimate daily feed intake. Feed expense was calculated by multiplying estimated dry matter intake by US$0.2341, which was the fixed cost of a kg of dry matter.

Replacement cost was variable for cows and differed based on age at first calving. The average age of first calving across breed types and years in this study was 23.4 months, and heifers calving the first time at 23.4 months had a replacement cost of US$1910. Heifers calving at younger or older ages had US$2.40 per day deducted or added to the replacement cost of US$1910. For lifetime replacement cost, the 2-breed crossbreds (US$1927) and their HO herdmates (US$1929) were similar. However, the 2-breed crossbreds (–US$0.20) had significantly lower replacement cost per day, because the replacement cost was distributed over more days in the herd compared with their HO herdmates (Table 9).

The 2-breed crossbreds (–13%) had significantly lower lifetime health treatment cost compared with their HO herdmates. Therefore, when lifetime cost was divided by days in the herd for each cow (Table 9), the 2-breed crossbreds averaged 29% lower daily health treatment cost compared with their HO herdmates.

Total daily expense was US$11.84 for the 2-breed crossbreds and US$12.19 for their HO herdmates (Table 9). The most important contributor to reduction of expenses for the 2-breed crossbreds was their lower replacement cost compared with their HO herdmates resulting from the longer days in the herd. The lower replacement cost was 57% of the total difference in expense for the combined 2-breed crossbreds compared with their HO herdmates.

The VR×MO/HO 3-breed crossbreds had 3% less daily income from production compared with their HO herdmates. However, the MO×VR/HO 3-breed crossbreds had 1% more daily income from production compared with their HO herdmates (Table 10). Daily calf value averaged US$0.06 more for the combined 3-breed crossbreds compared with their HO herdmates. Lifetime cull value was higher for the VR×MO/HO 3-breed crossbreds (US$944) and the MO×VR/HO 3-breed crossbreds (US$953) compared with their HO herdmates (US$814). However, the 3-breed crossbreds averaged 147 days longer in the herd compared with their HO herdmates. Therefore, the average cull value on a daily basis was US$0.01 lower for the VR×MO/HO 3-breed crossbreds and +US$0.03 higher for the MO×VR/HO 3-breed crossbreds and was not a major contributor to the difference in profit between the breed types. The combined 3-breed crossbreds had 1% lower daily income (US$16.13) compared with their HO herdmates (US$16.23). The 3-breed crossbreds had fewer lengthy lactations and calved back sooner each lactation compared with their HO herdmates. Therefore, the estimated feed intake for maintenance of the crossbred cows was lower because the crossbred cows had more days near peak production during their lifetimes compared with their HO herdmates.

Lifetime replacement expense was significantly lower for the VR×MO/HO 3-breed crossbreds (US$1,887) and the MO×VR/HO 3-breed crossbreds ($1,902) compared with their HO herdmates (US$1,923) because of the younger age at first calving of the 3-breed crossbreds. Furthermore, the 3-breed crossbreds distributed costs over more days in the herd, and this resulted in a major reduction in daily replacement cost (–US$0.21) compared with their HO herdmates.

Table 10. Daily income and expense that contributed to daily profit for VR×MO/HO and MO×VR/HO 3-breed crossbreds compared with their HO herdmates.

		Difference from Holstein	
	Holstein	VR×MO/HO	MO×VR/HO
Cows (number)	250	109	117
Income (US$)			
Production	$15.09	–$.45**	+$.10**
Calf value	$.43	+$.07**	+$.05**
Cull value	$.72	–$.01**	+$.03**
Total income (US$)	$16.23	–$.38**	+$.18**
Percentage difference from Holstein		–2%	+1%
Expense (US$)			
Feed (during lactation)	$5.39	–$.16**	–$.04**
Lactation overhead	$4.20	–$.04**	–$.01
Replacement	$1.60	–$.26**	–$.16**
Dry cow overhead (including feed)	$.41	+$.03**	+$.01
Health treatment	$.25	–$.08**	–$.09**
Breeding	$.19	–$.02**	–$.02**
Total expense (US$)	$12.28	–$.52**	–$.33**
Percentage difference from Holstein		–4%	–3%

** $P \leq 0.01$ significantly different from Holstein.

Lifetime health treatment cost was 26% less for the 3-breed crossbreds (US$170) than for their HO herdmates (US$229), and daily health treatment cost was US$0.09 lower for the 3-breed crossbreds compared with their HO herdmates. Also, the lifetime breeding expense, which included semen, insemination fees, and supplies, was similar for the 3-breed crossbreds and their HO herdmates. However, average daily breeding expense for the 3-breed crossbreds (US$0.17) was lower than for their HO herdmates (US$0.19).

The 3-breed crossbreds (US$11.84) had 4% lower daily expenses compared with their HO herdmates (US$12.28). Difference for replacement cost was the most influential expense and was 48% of the total difference in expense between the combined 3-breed crossbreds compared with their HO herdmates.

All four of the crossbred breed types had significantly higher lifetime profit compared with their HO herdmates, and the difference ranged from +18% to +58% (Table 11). Both types of 2-breed crossbreds had significantly higher daily profit compared with their HO herdmates. The combined 2-breed crossbreds had 13% higher daily profit compared with their HO herdmates (Table 11). Likewise, the combined 3-breed crossbreds had 9% higher daily profit. This outcome may seem surprising because the 3-breed crossbreds had less fat + protein production compared with their HO herdmates. However, the lower expense of the 3-breed crossbreds compared with their HO herdmates resulted in an advantage for daily profit of the VR×MO/HO 3-breed crossbreds (+4%) and MO×VR/HO 3-breed crossbreds (+13%).

Table 11. Lifetime profit and daily profit for VR×HO and MO×HO 2-breed crossbreds and VR×MO/HO and MO×VR/HO 3-breed crossbreds compared with their HO herdmates.

		Difference from Holstein	
	Holstein	VR×HO	MO×HO
Cows (number)	640	376	358
Lifetime profit	$2,842	+$498†	+$1,638**
Percentage difference from Holstein		+18%	+58%
Daily profit	$3.74	+$.22**	+$.72**
Percentage difference from Holstein		+6%	+19%
		Difference from Holstein	
	Holstein	VR×MO/HO	MO×VR/HO
Cows (number)	250	109	117
Lifetime profit	$2,823	+$902*	+$938*
Percentage difference from Holstein		+32%	+33%
Daily profit	$3.95	+$.17**	+$.51**
Percentage difference from Holstein		+4%	+13%

† $P \leq 0.10$, * $P \leq 0.05$, ** $P \leq 0.01$ significantly different from Holstein.

Sensitivity Analysis for Feed Intake

The actual feed intake of individual cows was not available for cows in this study because the herds did not have the ability to collect individual feed intake. Production and stage of lactation were the only factors used to estimate feed intake of individual cows for this study, and no potential differences in feed intake or feed efficiency of the breed types were taken into account. However, previous research compared ProCROSS© crossbreds to their HO herdmates for feed intake during the initial 150 days of lactation (Shonka-Martin et al., 2019). Daily feed intake was recorded, converted to dry matter intake, and analyzed. The ProCROSS© cows had 4.8% less dry matter intake in first lactation and 6.5% less dry matter intake in second and third lactation compared with their HO herdmates with absolutely no difference in fat + protein production (kg).

The breed type differences for feed intake from the previous study were applied to this study to estimate the feed intake of cows and then were converted to feed cost. The result was a much larger advantage in daily profit for both the 2-breed crossbreds (+US$0.79 per day) and 3-breed crossbreds (+US$0.66 per day) compared with their HO herdmates. The higher daily profit of the 2-breed crossbreds (+21%) and the 3-breed crossbreds (+17%) compared with their HO herdmates, including their potential advantages for feed efficiency, may better reflect the actual daily profit of the ProCROSS© crossbreds compared with their HO herdmates in this study.

▪ Breeds for Rotational Crossbreeding

ProCROSS© is a 3-breed rotational program, and three distinct breeds provides an average hybrid vigour of 86% across generations. Use of only two breeds for crossbreeding provides an average hybrid vigour of 67% across generations, and this is a 17% reduction of average hybrid vigour from a 3-breed to 2-breed rotation. Choosing three breeds to include for rotational crossbreeding should be based on breeds that 1) have highly-effective genetic improvement programs that emphasize important traits for improved profitability, 2) best complement each other for individual traits, and 3) provide a blended outcome across generations that is most appropriate for the environmental conditions of a herd.

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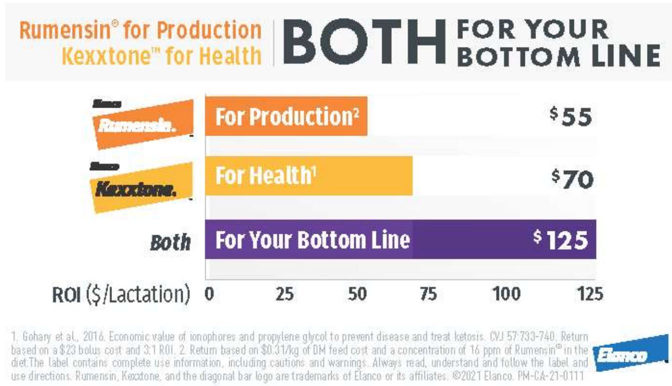
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