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Performance of purebred dairy cows and crossbred cows between Swedish Red, Swedish Holstein, Jersey, and Montbéliarde in Swedish herds

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Introduction: The use of dairy x dairy crossbreeding has increased in Sweden. This study aimed to compare crosses between Swedish Red (R), Holstein (H), Jersey (J), and Montbéliarde (M) to purebred R, H, and J for fertility, calving, production, and survival traits. The focus was on F1 crosses between either H or R on the one hand and J or M on the other hand, but three-breed crosses were also studied.

Material and methods: There were 2,154,241 observations collected from the official cattle recording database for cows that calved between 2005 and 2020 in 7,390 herds. The dataset was separated into first and second parity and analyzed using a mixed linear model including fixed effects of breed group, herd, and year-season and a random effect of herd-year.

Results and discussion: Fertility traits were improved in the F1 crosses with J or M compared with R or H (i.e., JR and MR vs. R; JH and MH vs. H), especially in the first parity. In parity 2, the difference was often not significant. Crossing R or H with Jersey gave lower calving difficulty than in the pure breeds in the first parity. However, crossing with Montbéliarde rather tended to give slightly more calving difficulties, albeit not significantly so. Generally, there was no significant change in stillbirths when crossing purebred R or H with J or M. There was a general tendency for better survival in the F_1-crosses, however, only significantly so for Jersey crosses in parity 2 with respect to R or H. F_1 between J and H (JH) had a higher 305-day fat yield than H, but lower milk and protein yields. MH had higher fat and protein yields than H and MR had higher 305-d milk and protein yields than R. In conclusion, crossing R or H with either Jersey or Montbéliarde can be expected to improve fertility and probably also survival. Depending on the current situation, one could choose to improve fat yield (crossing with J) or protein yield (crossing with M), however, depending on the breed, there could be a trade-off, e.g., in milk yield. For other traits, one would not expect any deterioration.

KEYWORDS

dairy cattle, crossbreeding, milk production, fertility, calving difficulty, stillbirth, survival

1 Introduction

In some livestock species, such as pigs and poultry, crossbreeding is the main breeding strategy. The crossing of strains or breeds is done to make use of complementarity and heterosis of traits and generally results in more robust offspring with better health, growth, fertility, and production. In dairy cattle, crossbreeding has also been shown to improve functional traits such as fertility, health, calving ability, and survival (e.g., Sorensen et al., 2008; Clasen et al., 2017; Hazel et al., 2017). However, crossbreeding between dairy cattle breeds is relatively uncommon in European countries (Dezetter et al., 2017; Clasen et al., 2019), the United States of America (USA), and Canada (Norman et al., 2018), whereas crossbreeding is a major breeding strategy in New Zealand (DairyNZ, 2021). Studies on the economic benefits of systematic crossbreeding have been sparse, but recent studies have shown economic benefits (Dezetter et al., 2017; Shonka-Martin et al., 2019; Clasen et al., 2020a, b).

Crossbred dairy cows are becoming more common in Sweden. In 2013, 7.5% of all calves born were crosses between the two largest dairy breeds in Sweden, Holstein and Swedish Red (Växa, 2014). In 2022, that prevalence had increased to 9.5% (Växa, 2023). The breeding company VikingGenetics, which has a market share of approximately 80% in Sweden, promotes two rotational crossbreeding systems: ProCross and GoldenCross. ProCross is a cross between Holstein, Viking Red, and Montbéliarde, and the GoldenCross is a cross between Holstein, Viking Red, and Jersey (VikingGenetics, 2024). Viking Red is the name VikingGenetics uses for the breeds Swedish Red, Danish Red, and Finnish Ayrshire (Freddy Fikse, personal communication). Records from Växa's cattle database show that ProCross came to Sweden in the 2000s, which contributed to an increased use of Montbéliarde sires. Jersey and Brown Swiss are also being used in Swedish crossbred dairy cows. Even though the prevalence of Montbéliarde and Jersey crossbred cows is increasing in Sweden, no analysis has yet been done on their performance compared with purebred Holstein or Swedish Red. However, crosses between Holstein and Swedish Red have been compared to purebred Swedish Red and Holstein for functional traits and production traits (Jönsson, 2015). Multiple studies of Montbéliarde crossbred cows have been done in the USA. The studies generally found that the Montbéliarde crossbred cows had improved fertility and better survival than purebred US Holstein (Heins et al., 2006b; Hazel et al., 2020a; b, 2021).

In the Swedish case, with Swedish Red and Holstein being the dominant breeds, the most interest is in crossing them with another breed, e.g., Jersey or Montbéliarde, either to create an F_1 in part of the herd or as a first step in a rotational crossbreeding system (Clasen et al., 2020a, b). Thus, this study aimed to compare two-way and three-way crosses between Swedish Red, Holstein, Jersey, and Montbéliarde to purebred Holstein, Swedish Red, and Jersey. The main focus was on two-way and three-way crosses between Holstein and Swedish Red on the one hand and Jersey or Montbéliarde on the other hand. The traits used in this study were related to fertility, calving, production, and survival. The overall hypothesis was that the crossbred cows would perform better than the purebred cows.

2 Material and methods

Data were provided by Växa from their cattle database. Records in the cattle database were collected from Swedish dairy farms. In this study, the focus was on Swedish Red (R), Holstein (H), Jersey (J), Montbéliarde (M), and crosses between them. However, other crossbreed groups were also available, resulting in 29 different breed groups (Table 1). The breed group R included the breeds Danish Red, Swedish Ayrshire, and Swedish Red. The sire was required to be purebred and the dam was either purebred or two-way crossbred. The crossbred cows were either two-way crosses or three-way crosses. For the two-way and three-way crosses, no difference was made if the sire was one breed and the dam another breed or vice versa. For instance, HR (sire by dam) or RH are both treated as a cross between Holstein and Swedish Red and referred to as HR. The three-way cross was also written as sire breed x crossbred dam, where the sire is purebred and the dam is crossbred, e.g., MxHR.

Records were collected for cows with calving dates in the first and second parity between 1 January 2005, and 31 December 2020, including 2,751,640 observations. Because all the records were collected from historical field data, no ethical approval was needed. We removed purebred Montbéliarde cows because they were too few (fewer than 300) and Brown Swiss because the coding does not guarantee that they are purebred. In the three-way crosses, breed crosses with fewer than 50 observations were removed from the study. After editing 2,154,241 observations and 7,390 herds were included in the study. Two datasets were created: for parity 1 with 1,203,399 observations and for parity 2 with 950,842 observations (the number of observations per breed group is shown in Table 1). Approximately 75% of the herds had more than one breed group (including crossbreeds) creating good connections among the herds for an estimation of breed group effects.

2.1 Traits and statistical analysis

The fertility traits included were: calving interval (CI), calving to first insemination interval (CFI), calving to last insemination interval (CLI), first to last insemination interval (FLI), and number of inseminations per series (NINS). The allowed range of values were set to 280–650 d, 20–230 d, 20–450 d, 0–365 d, and 1–8, respectively. If any of the observation values were outside these intervals, the value was set to missing. The sixth trait was the age at first calving (AFC) for which no limits were set, but the interval was between 578 and 1,156 d (19 and 39 months).

There were two calving traits included, calving difficulty and stillbirth. The scoring of calving difficulty was slightly changed during our study period. Prior to 2012, calving performance was recorded as easy, difficult, or malpresentation. A new scoring system was then gradually introduced until the end of 2016, and thereafter only the new calving categories, namely, easy without assistance, easy with assistance, difficult without veterinary assistance, or difficult with veterinary assistance, were used. In this study, calving difficulty was defined in three classes: easy (scored as easy in the old system, or as easy calving, without or with assistance in

TABLE 1 The total number of observations (cows) for the different breed groups (breed of sire followed by breed (group) of dam) with at least one trait observed in parity 1 and parity 2.

Breed group[1]	Parity 1	Parity 2
R	488,549	388,574
H	618,794	481,157
J	7,994	6,024
HR	35,545	31,877
JR	1,077	905
JH	1,113	913
MR	361	186
MH	827	369
BR	228	178
BH	315	190
BxHR	155	109
HxBH	238	164
HxBR	76	55
HxHR	32,812	27,774
HxJH	816	689
HxJR	250	196
HxMH	168	105
HxMR	311	140
JxHR	300	217
JxJH	378	264
JxJR	536	415
MxHR	1,436	813
RxBH	70	67
RxBR	98	66
RxHR	9,425	8,223
RxJH	236	213
RxJR	832	701
RxMH	343	181
RxMR	116	77

[1] R, Swedish Red; H, Holstein; J, Jersey; B, Brown Swiss; M, Montbéliarde.
Breed groups in bold type are the main focus of the study.

the current system); difficult (scored as difficult calving or malpresentation in the old system, or as difficult calving, without or with veterinary assistance in the current system); or missing (all other scores or missing score). Stillbirth was defined as 1 if the calf was dead at birth or within 24 h after birth, and 0 otherwise.

The production traits were based on milk yield, fat yield, and protein yield data from test days. The yield was assumed to be the same between the midway point of the previous test day to the midway point of the next test day. The first test day yield was assumed to be valid back to day 3 after calving. Similarly, the last test day yield was assumed to be valid up to 15 days after the last test day. The traits 305-d milk yield (MY305), 305-d fat yield (FAT305), and 305-d protein yield (PROT305) were calculated by adding the yields for 305 days starting from day 3. If the criteria of 305 days of lactation were not fulfilled, the records were not included for these traits. Energy-corrected milk was calculated as ECM305 = 0.25 × MY305 + 12.2 × FAT305 + 7.7 × PROT305, following Sjaunja et al. (1990).

Somatic cell count was also measured every test day. Logarithmic (to base 10) somatic cell count (LSCC) was used in this study to cause the somatic cell count to be more normally distributed. The average LSCC over 305 days (LSCC305) was calculated by adding the LSCC for 305 days starting from day 3 and then dividing by 305, using the same approach as for yield traits. Lastly, survival was defined as 0 for not surviving to the next lactation and 1 as surviving to the next lactation.

Editing, definition of traits, and descriptive analyses were done in SAS 9.4 (SAS Institute, 2013) and in R statistical software (R Core Team, 2021). R was also used to get the compact letter display of the significance of differences from the SAS output as it is not given in Proc HPMIXED. Parity 1 and parity 2 were analyzed separately in SAS with the Proc HPMIXED procedure applying REML for estimation of random effects. The following mixed linear model was used:

$$y_{ijlmn} = \mu + b_i + h_j + ys_{lm} + hy_{jl} + e_{ijlmn} \quad (1)$$

where y_{ijlmn} = value of the trait; b_i = fixed effect of breed group i (1–29); h_j = fixed effect of herd j (1–7,129 for parity 1, 1–7,123 for parity 2); ys_{lm} = fixed effect of year l (2005–2020) and season m (1 = March–May; 2 = June–August; 3 = September–November; 4 = December–February) combination (1–64); hy_{jl} = the random effect of herd j and year l (2005–2020) combination ~ $N(0,\sigma^{2hy})$, (1–62,010 for parity 1, 1–63,583 for parity 2); and e_{ijlmn} = random residual effect ~ N $(0,\sigma^{2e})$. Differences between the various breed group least squares means were tested using a t-test and a nominal p-value of 0.05.

Heterosis was calculated based on F_1 performance and, therefore, it was only possible to calculate for JR, JH, and HR in relation to the average of the pure breeds.

3 Results

Averages and standard deviations across all breed groups are shown in Table 2.

3.1 Jersey crosses

The results for all traits for H, R, and J, and their crosses are presented in Table 3 for both parities. The results for some of the traits are graphically shown in Figure 1. For the first parity, JR had significantly better fertility than purebred R and J. JH had better fertility than H (CI, CFI, CLI, FLI, and NINS), but generally not significantly better than J. Mainly, the three-breed crosses (HxJR,

TABLE 2 Overall means and standard deviations[1] for parity 1 and parity 2 across all breed groups.

	Parity 1		Parity 2	
Trait[2]	Mean	SD	Mean	SD
CI	397.8	58.9	396.3	56.3
CFI	86.3	33.5	85.3	33.2
CLI	129.2	68.7	127.8	65.8
FLI	40.6	60.4	40.5	58.0
NINS	1.97	1.28	1.99	1.27
AFC	833	83.1	–	–
Calving diff.	3.72	18.7	1.20	10.8
Stillbirth	6.45	24.4	3.41	18.1
Survival	70.1	44.5	60.7	47.7
MY305	8,875	1281	10,281	1457
FAT305	368.7	52.1	427.5	61.5
PROT305	306.4	41.5	356.8	48.2
ECM305	9,075	1,119	10,496	1,374
LSCC305	1.72	0.38	1.87	0.54

[1]Calculated as the square root of the sum of the estimates of herd-year variance and residual variance from the model [1].
[2]CI, calving interval in days; CFI, calving to first insemination in days; CLI, calving to last insemination in days; FLI, first to last insemination in days; NINS, number of inseminations; AFC, age at first calving in days; calving difficulty, stillbirth, and survival to second or third calving in percentages; MY305, FAT305, and PROT305 = milk, fat, and protein yields in kg over 305 d; LSCC305 = average $\log_{10}$ somatic cell count in 1,000 cells over 305 d.

JxHR, and RxJH) did not have better fertility than the three pure breeds, except for CI, where all were better than H. In parity 2, JH was still better than H for these 5 fertility traits, and JR was mostly better than J (except for CFI). For AFC, J was the oldest at first calving, and JH had a higher AFC than H.

Of the pure breeds, Jersey had the lowest calving difficulty. JR and JH had lower calving difficulty than pure breeds in first parity, although the difference with J was not significant. In parity 2, calving difficulties were rare, but JH was better than H; otherwise, no significant differences were found. Stillbirth rates were highest for J, and JR and JH had a lower stillbirth rate in the first parity than purebred J. Most three-breed crosses also had a lower stillbirth rate than J. In parity 2, JH and JR had a lower stillbirth rate than purebred J.

Survival in first parity was lowest for J. JR had higher survival than J and JH had higher survival than both J and H. In the second parity, JR had higher survival than both R and J, and JH had higher survival than H.

Both JR and JH had higher 305-d milk, fat, protein, and ECM yields than purebred J in all parities. JR and JH had higher 305-d fat yield than purebred R or H, respectively; however, JR and JH had lower milk and protein yields than R and H, respectively. For ECM305, there was no significant difference, except that JH had lower ECM305 than H in the second parity. In addition, the three-breed crosses had higher milk, fat, protein, and ECM yields than J in all parities. Also, in the first parity, the three-breed crosses had a higher fat yield than the three pure breeds and a higher ECM305 than R and J. The crosses JR and JH had significantly higher LSCC305 than R or H, respectively, in parity 1, whereas in parity 2 the difference was not significant. However, JR had lower LSCC305 than purebred J in both parities.

3.2 Montbéliarde crosses

The results for all traits are presented for H, R, M, and the crosses between them in Table 4 for both parities. The results for some of the traits are graphically shown in Figure 2. For the first parity, MR had better CLI, FLI, and NINS than R, and MH had better CI, CFI, and CLI than H. Among the three-breed crosses, only MxHR had better fertility than H (all five traits). In parity 2, MR was better than R for all fertility traits except CFI. The three-breed crosses never had better fertility than purebred R but were often better than H.

Calving difficulty was not significantly different between MR and R or between MH and H in either parity. Regarding the three-breed crosses, HxMR had more calving difficulties than R and MxHR, and RxMH had lower rates than H in the first parity. Regarding parity 2, the general level of calving difficulty was much lower, however, MxHR had lower calving difficulty than H. Stillbirth rates were generally not different between the crosses and the pure breeds in either the first or second parities. There was no difference in survival in any lactation between MR and R or between MH and H. Both HxMR and MxHR, however, had higher survival than R or H in the first parity; in the second parity, that was only true for MxHR with respect to H.

MR had higher 305-d milk and protein yields than R, and MH had higher 305-d fat and protein yields than H in the first parity. All three-breed crosses had higher 305-d milk and protein yield than R; HxMR and MxHR also had higher fat and ECM yields than R. None of the three-breed crosses had higher 305-d yields than H, except for HxMR for fat yield and ECM. In the second parity, a similar pattern was seen, but MR also had higher ECM305 than R, and the three-breed crosses had more commonly significantly lower yields than H. There was no significant difference between MR or MH and purebred R or H, respectively, for LSCC305 in either parity, and the three-breed crosses were generally not different from R or H.

3.3 Holstein x Swedish Red crosses

The fertility traits CI, CFI, CLI, FLI, and NINS were significantly better for HR than H in both the first and second lactations. However, compared with R, HR only had a slightly lower NINS in the first parity; otherwise, HR had worse fertility than R in parity 2, except for a slightly shorter CFI. Age at first calving was, however, lower for HR than for the pure breeds.

Calving difficulties and stillbirths were lower for HR than for H, but higher than for R (or not different, for parity 2). Survival in the first and second parities was better for HR than the purebreds. HR had generally higher 305-d yields than R but lower yields than H, in both parities. The exceptions were the 305-d fat yield in the first

TABLE 3 Least squares means[1] for all traits and nine different breed groups[2] (three pure breeds (R, H, and J), three two-breed crosses (HR, JR, and JH), and three three-breed crosses (HxJR, JxHR, and RxJH)) for cows in parity 1 and 2.

		Breed group								
Parity	Trait[3]	R	H	J	HR	JR	JH	HxJR	JxHR	RxJH
First	CI	405^{ab}	412^{c}	406^{b}	406^{b}	399^{d}	402^{bd}	397^{ad}	400^{bd}	401^{bd}
	CFI	95^{a}	98^{b}	94^{a}	96^{c}	90^{d}	94^{ac}	91^{ad}	96^{abc}	92^{acd}
	CLI	140^{ab}	149^{c}	140^{ab}	141^{b}	131^{d}	136^{ad}	138^{bd}	143^{abc}	133^{bd}
	FLI	41^{a}	45^{b}	42^{a}	40^{a}	36^{c}	38^{ac}	42^{abc}	43^{abc}	39^{abc}
	NINS	1.96^{a}	2.02^{b}	2.02^{b}	1.93^{c}	1.88^{c}	1.90^{ac}	1.93^{abc}	1.87^{abc}	1.85^{abc}
	AFC	859^{a}	856^{b}	874^{c}	851^{d}	857^{ab}	867^{e}	846^{d}	858^{abde}	849^{abd}
	CD	3.0^{a}	4.4^{b}	2.1^{c}	3.6^{d}	1.5^{c}	1.8^{c}	2.0^{acd}	2.5^{abcd}	2.4^{abcd}
	SB	4.6^{a}	7.4^{b}	10.0^{c}	5.5^{de}	5.4^{ad}	6.0^{abe}	2.8^{ae}	6.5^{abe}	8.0^{bcd}
	Survival	55.9^{a}	57.0^{b}	53.9^{c}	59.6^{d}	58.6^{abd}	59.7^{d}	59.9^{abd}	55.1^{abcd}	56.4^{abcd}
	MY305	$7{,}999^{a}$	$8{,}779^{b}$	$6{,}097^{c}$	$8{,}575^{d}$	$7{,}358^{e}$	$7{,}844^{f}$	$8{,}278^{g}$	$7{,}492^{e}$	$7{,}927^{af}$
	FAT305	350^{a}	356^{b}	356^{b}	361^{c}	375^{d}	383^{e}	375^{de}	378^{de}	368^{cd}
	PROT305	283^{a}	298^{b}	244^{c}	296^{d}	275^{e}	288^{f}	292^{bdf}	280^{ae}	288^{af}
	ECM305	$8{,}455^{a}$	$8{,}828^{b}$	$7{,}753^{c}$	$8{,}827^{b}$	$8{,}537^{ad}$	$8{,}850^{b}$	$8{,}889^{be}$	$8{,}644^{de}$	$8{,}687^{bd}$
	LSCC305	1.71^{a}	1.75^{b}	1.87^{c}	1.73^{d}	1.79^{e}	1.81^{e}	1.76^{abde}	1.83^{ce}	1.71^{abd}
Second	CI	397^{a}	410^{b}	401^{c}	401^{c}	393^{a}	395^{a}	402^{abc}	396^{ac}	396^{ac}
	CFI	91^{a}	97^{b}	90^{a}	93^{c}	89^{a}	91^{ac}	92^{ac}	92^{abc}	92^{abc}
	CLI	131^{a}	147^{b}	131^{a}	136^{c}	126^{d}	130^{ad}	130^{acd}	125^{ad}	131^{acd}
	FLI	37^{ab}	46^{c}	39^{ad}	39^{d}	33^{b}	37^{bd}	35^{bd}	29^{b}	36^{bd}
	NINS	1.89^{ab}	2.04^{c}	1.92^{ad}	1.91^{d}	1.82^{b}	1.88^{bd}	1.76^{bd}	1.79^{bd}	1.76^{bd}
	CD	1.12^{ab}	1.37^{c}	0.77^{b}	1.23^{a}	0.94^{abc}	0.45^{b}	1.67^{abc}	0.18^{abc}	1.05^{abc}
	SB	3.14^{ab}	3.25^{b}	4.88^{c}	2.93^{a}	3.36^{ab}	3.05^{ab}	1.49^{ab}	4.49^{abc}	3.77^{abc}
	Survival	49.9^{a}	48.4^{b}	51.6^{ac}	52.7^{c}	58.0^{d}	52.9^{ac}	57.7^{cd}	51.0^{abcd}	56.3^{cd}
	MY305	$9{,}048^{a}$	$10{,}221^{b}$	$6{,}879^{c}$	$9{,}831^{d}$	$8{,}261^{e}$	$8{,}742^{f}$	$9{,}292^{a}$	$8{,}515^{ef}$	$9{,}068^{a}$
	FAT305	394^{a}	415^{b}	405^{c}	413^{d}	420^{be}	433^{f}	417^{bde}	431^{ef}	414^{bcd}
	PROT305	323^{a}	349^{b}	281^{c}	341^{d}	314^{e}	329^{f}	330^{af}	322^{aef}	331^{f}
	ECM305	$9{,}556^{a}$	$10{,}279^{b}$	$8{,}819^{c}$	$10{,}117^{d}$	$9{,}613^{ae}$	$9{,}991^{f}$	$9{,}967^{df}$	$9{,}837^{ef}$	$9{,}877^{f}$
	LSCC305	2.01^{a}	2.07^{bc}	2.12^{d}	2.04^{e}	2.04^{ace}	2.10^{bd}	2.01^{ace}	2.10^{cde}	2.02^{ace}

[1] Pairs of breed groups differ significantly ($P < 0.05$) if no superscripts are in common.
[2] R, Swedish Red; H, Holstein; J, Jersey.
[3] CI, calving interval in days; CFI, calving to first insemination in days; CLI, calving to last insemination in days; FLI, first to last insemination in days; NINS, number of inseminations; AFC, age at first calving in days; CD, calving difficulty in percentages; SB, stillbirth in percentages; survival to second calving in percentages; MY305, FAT305, and PROT305 = milk, fat, and protein yields in kg over 305 d; LSCC305 = average $\log_{10}$ somatic cell count in 1,000 cells over 305 d.

parity, which was higher for HR than for H, and ECM305, which did not differ between HR and H. Somatic cell count was higher for HR than R in both parities, but lower than for H.

3.4 Heterosis

The amount of heterosis based on F_1 performance in relation to the average of the pure breeds was only possible to calculate for JR, JH, and HR (Table 5). The largest heterosis was found for calving difficulty and stillbirth, however, this was most likely influenced by the very low average values for these traits. Fertility traits and yield traits had similar heterosis values, approximately 4–6% for JH and JR, and approximately 2% for HR, whereas survival had heterosis from 6% to 14% regardless of the type of F_1-cross. The average (absolute) heterosis across all traits was larger for JH and JR (approximately 6–10%) than for HR (approximately 3%).

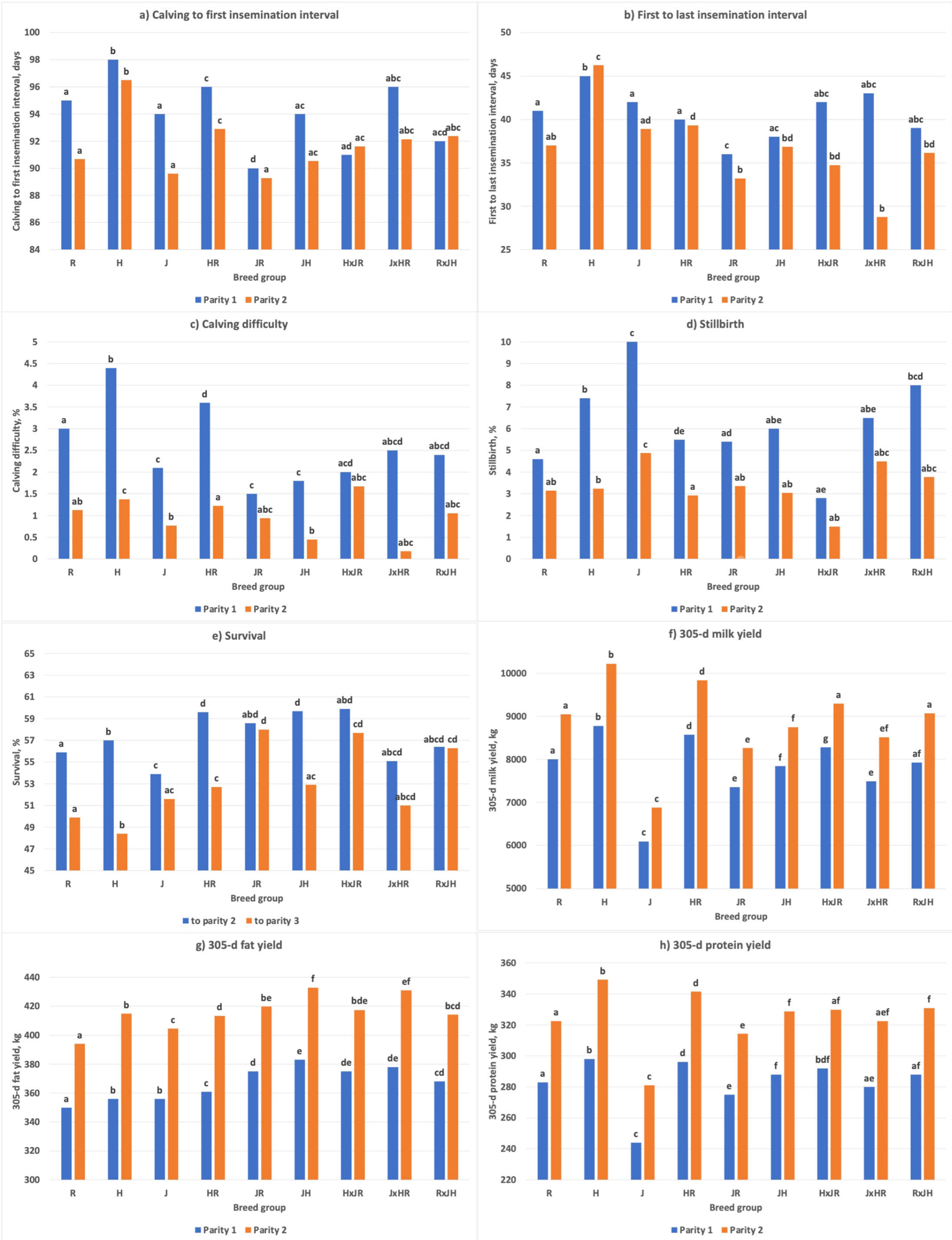

FIGURE 1
Least squares means for eight traits and nine different breed groups (three pure breeds (R, Swedish Red; H, Holstein; J, Jersey), three two-breed crosses (HR, JR, JH), and three three-breed crosses (HxJR, JxHR, RxJH)) for cows in parity 1 and 2. Pairs of breed groups differ significantly ($P < 0.05$) within a parity if no superscripts are in common. **(A)** Interval from calving to first insemination in days; **(B)** interval from first to last insemination in days; **(C)** calving difficulty in percentages; **(D)** stillbirth in percentages; **(E)** survival to second or third calving in percentages; **(F)** 305-d milk yield in kg; **(G)** 305-d fat yield in kg; **(H)** 305-d protein yield in kg.

TABLE 4 Least squares means[1] for all traits and eight different breed groups[2] (two pure breeds (R and H), three two-breed crosses (HR, MR,and MJH), and three three-breed crosses (HxMR, MxHR, and RxMH)) for cows in parity 1 and 2.

		Breed group[2]							
Parity	Trait[3]	R	H	HR	MR	MH	HxMR	MxHR	RxMH
First	CI	405^{a}	412^{b}	406^{a}	401^{a}	406^{a}	408^{ab}	402^{a}	409^{ab}
	CFI	95^{a}	98^{b}	96^{c}	93^{ac}	93^{ac}	95^{abc}	94^{ac}	97^{abc}
	CLI	140^{a}	149^{b}	141^{a}	132^{c}	142^{a}	139^{ac}	138^{ac}	143^{abc}
	FLI	41^{a}	45^{b}	40^{ac}	33^{c}	43^{ab}	40^{abc}	39^{ac}	40^{abc}
	NINS	1.96^{a}	2.02^{b}	1.93^{cd}	1.80^{d}	1.97^{abc}	1.88^{abd}	1.90^{ad}	1.92^{abd}
	AFC	859^{a}	856^{b}	851^{c}	844^{cd}	841^{d}	846^{cd}	844^{d}	839^{d}
	CD	3.0^{a}	4.4^{b}	3.6^{cd}	4.3^{abd}	4.5^{bd}	5.3^{bd}	3.2^{ad}	1.7^{ac}
	SB	4.6^{a}	7.4^{b}	5.5^{cd}	5.9^{abd}	6.8^{bd}	6.0^{abd}	5.5^{ad}	3.5^{ac}
	Survival	55.9^{a}	57.0^{b}	59.6^{cd}	55.9^{abc}	58.5^{abd}	63.6^{d}	59.9^{cd}	57.7^{abd}
	MY305	7,999^{a}	8,779^{b}	8,575^{cd}	8,438^{de}	8,837^{b}	8,724^{bc}	8,751^{b}	8,280^{e}
	FAT305	350^{a}	356^{bc}	361de	349^{ac}	361de	368^{e}	359^{bd}	350^{ac}
	PROT305	283^{a}	298^{b}	296^{c}	291^{cd}	303^{e}	303^{be}	300^{be}	290^{d}
	ECM305	8,455^{a}	8,828^{b}	8,827^{b}	8,594^{a}	8,940^{bc}	9,001^{c}	8,874^{bc}	8,564^{a}
	LSCC305	1.71^{a}	1.75^{b}	1.73^{c}	1.70^{abc}	1.75^{bc}	1.71^{abc}	1.75^{bc}	1.71^{abc}
Second	CI	397^{a}	410^{b}	401^{c}	379^{d}	403^{abc}	395^{acd}	400^{ac}	394^{ac}
	CFI	91^{abc}	97^{d}	93^{e}	86^{b}	91^{be}	94^{cde}	89^{bc}	95^{ade}
	CLI	131^{a}	147^{b}	136^{c}	120^{d}	140^{c}	137^{abc}	133^{ac}	128^{acd}
	FLI	37^{ab}	46^{c}	39^{d}	27^{e}	45^{cd}	38^{bcde}	40^{bd}	29^{ae}
	NINS	1.89^{ab}	2.04^{c}	1.91^{de}	1.65^{f}	2.09^{c}	1.79^{bef}	1.97^{bce}	1.75^{adf}
	CD	1.12^{a}	1.37^{b}	1.23^{a}	1.77^{ab}	1.58^{ab}	1.47^{ab}	0.53^{a}	0.74^{ab}
	SB	3.14^{ab}	3.25^{b}	2.93^{a}	1.01^{ab}	3.06^{ab}	4.15^{ab}	2.29^{ab}	3.48^{ab}
	Survival	49.9^{a}	48.4^{b}	52.7^{c}	55.7^{ac}	52.8^{abc}	52.4^{abc}	52.9^{ac}	54.7^{abc}
	MY305	9,048^{a}	10,221^{b}	9,831^{cd}	9,598^{d}	10,354^{b}	10,094^{bc}	9,859^{cd}	9,535^{d}
	FAT305	394^{a}	415^{b}	413^{c}	398^{ad}	424^{e}	429^{e}	405^{d}	396^{ad}
	PROT305	323^{a}	349^{b}	341^{c}	333^{cd}	359^{e}	352^{be}	341^{cd}	331^{ad}
	ECM305	9,556^{a}	10,279^{b}	10,117^{c}	9,836^{d}	10,440^{b}	10,501^{b}	10,036^{cd}	9,791^{ad}
	LSCC305	2.01^{ab}	2.07^{c}	2.04^{d}	1.96^{b}	2.05^{acd}	2.03^{bcd}	2.04^{bcd}	2.04^{bcd}

[1] Pairs of breed groups differ significantly ($P < 0.05$) if no superscripts are in common.
[2] R, Swedish Red; H, Holstein; M, Montbéliarde.
[3] CI, calving interval in days; CFI, calving to first insemination in days; CLI, calving to last insemination in days; FLI, first to last insemination in days; NINS, number of inseminations; AFC, age at first calving in days; CD, calving difficulty in percentages; SB, stillbirth in percentages; survival to second calving in percentages; MY305, FAT305, and PROT305 = milk, fat, and protein yields in kg over 305 d; LSCC305 = average $\log_{10}$ somatic cell count in 1,000 cells over 305 d.

4 Discussion

4.1 Jersey crosses

4.1.1 Fertility traits

In general, fertility interval traits and NINS were improved in the F_1 crosses with J compared with purebred R or H, especially in the first parity. In parity 2, the difference was often not significant, e.g., for JR vs. R in parity 2; however, the numerical difference was in the same direction, or there was no substantial difference. Thus, a first-generation cross with J is expected to improve fertility or at least not impair it. The (significant) changes in the interval traits were in the range of 4 to 17 days, corresponding to a range of 0.12 to 0.28 SD units.

Heins et al. (2012) compared Jersey x Holstein to Holstein and found that the calving to first insemination was significantly shorter for Jersey x Holstein in the first three lactations, similar to our findings. They also found fewer NINS in the second parity and fewer days open (CLI) in all three lactations. However, our results disagree with McClearn et al. (2020) who found that Jersey x Holstein had

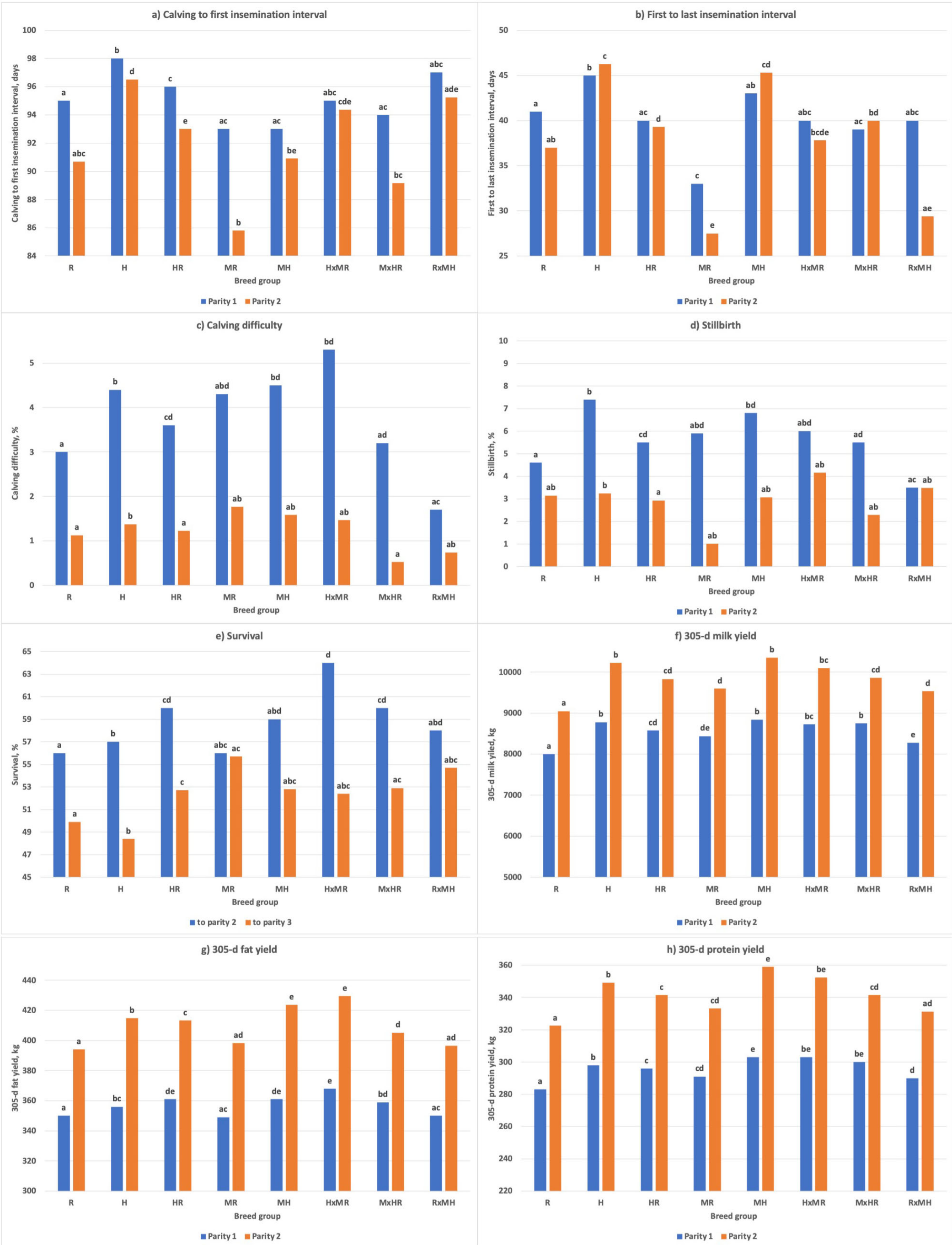

FIGURE 2
Least squares means for eight traits and eight different breed groups (three purebreds (R, Swedish Red; H, Holstein; M, Montbéliarde – not shown owing to too few animals), three two-breed crosses (HR, MR, MH), and three three-breed crosses (HxMR, MxHR, RxMH)) for cows in parity 1 and 2. Pairs of breed groups differ significantly (P < 0.05) within a parity if no superscripts are in common. **(A)** Interval from calving to first insemination in days; **(B)** interval from first to last insemination in days; **(C)** calving difficulty in percentages; **(D)** stillbirth in percentages; **(E)** survival to second or third calving in percentages; **(F)** 305-d milk yield in kg; **(G)** 305-d fat yield in kg; **(H)** 305-d protein yield in kg.

significantly longer calving to first insemination compared to Holstein in a spring-calving herd under Irish conditions. They found no significant differences for other fertility traits.

For the three-breed crosses with J, the fertility results were more variable. Most comparisons with the three pure breeds were not significant, owing to the fewer number of animals in the three-breed cross groups. However, the significant differences were in favor of the three-breed crosses. Therefore, although results were not as clear as for the F_1 crosses, these three-breed crosses are at least not expected to decrease fertility.

The results for age at first calving were largely influenced by the higher AFC for Jersey, more than 2 weeks higher than the other

TABLE 5 Heterosis[1] (%) for all traits and absolute average heterosis (Abs. ave.) across all traits from three different F_1-crosses for parity 1 and 2.

Trait[3]	Parity					
	1			2		
	Breed group[2]					
	JR	JH	HR	JR	JH	HR
Abs. ave.	9.1	9.9	2.9	5.7	10.5	2.8
CI	−1.6	−1.7	−0.6	−1.5	−2.7	−0.6
CFI	−4.8	−2.1	−0.5	−1.0	−2.7	−0.7
CLI	−6.4	−5.9	−2.4	−4.4	−6.4	−2.1
FLI	−13.3	−12.6	−7.0	−12.5	−13.5	−5.6
NINS	−5.5	−5.9	−3.0	−4.6	−4.9	−2.6
AFC	−1.1	0.2	−0.8			
CD	−41.2	−44.6	−2.7	−0.3	−58.2	−1.6
SB	−26.0	−31.0	−8.3	−16.2	−24.9	−8.4
Survival	7.3	8.1	6.2	14.3	5.8	7.2
MY305	4.4	5.5	2.2	3.7	2.3	2.0
FAT305	6.2	7.6	2.3	5.1	5.6	2.2
PROT305	4.4	6.3	1.9	4.2	4.3	1.6
ECM305	5.3	6.7	2.1	4.6	4.6	2.0
LSCC305	0.0	0.0	0.0	−1.5	0.3	0.0

[1] Calculated as [AB − (A+B)/2]/[(A+B)/2], where A and B are the two pure breed values and AB is the F_1-value for the trait in question.
[2] JR, F_1 cross between Jersey and Swedish Red; JH, F_1 cross between Jersey and Holstein; HR, F_1 cross between Holstein and Swedish Red.
[3] CI, calving interval in days; CFI, calving to first insemination in days; CLI, calving to last insemination in days; FLI, first to last insemination in days; NINS, number of inseminations; AFC, age at first calving in days; CD, calving difficulty in percentages; SB, stillbirth in percentages; survival to second calving in percentages; MY305, FAT305, and PROT305 = milk, fat, and protein yields in kg over 305 d; LSCC305 = average $\log_{10}$ somatic cell count in 1,000 cells over 305 d.

purebreds. Although the crosses were younger than purebred J, this change was not large enough for these crossbreds to be younger than purebred R or H. We have not been able to make any comparisons with the literature for this trait.

4.1.2 Calving traits and survival

The results for calving difficulty and stillbirth for the Jersey crosses were clearly influenced by the levels for the purebred J, having the lowest calving difficulty, but the highest stillbirth rate among the pure breeds. Because J was better than R and especially H for calving difficulty, F_1 crosses with J were also better than R and H, respectively, but not significantly better than purebred J. In parity 2, JR was not significantly better than R, however. The only comparison in the literature we could find was McClearn et al. (2020), who did not find any difference between Jersey x Holstein and Holstein in calving difficulty.

Similarly, but in the opposite way, J had the highest stillbirth rate so crosses with R and H generally significantly decreased stillbirth rates, but not to the extent of making F_1 crosses better than purebred R or H.

Heins et al. (2012) reported a 14% higher survival ($p < 0.1$) for Jersey x Holstein crossbreds compared with purebred Holstein from first to third calving. We found a difference of 3% and 5% difference in survival in the first and second parities, respectively. The difference may be connected to the fewer cows (80) in Heins et al. (2012).

The interpretation of results regarding survival and longevity is often complicated, especially in a study based on real herd data, because survival is very much influenced by farmer decisions. For instance, if a farmer decides to start crossbreeding, it might influence their decision to cull or not a crossbred cow, i.e., maybe the risk of culling becomes lower for a crossbred cow, all else being equal. However, not all crossbred cows are part of a long-term plan to convert to a crossbreeding system, and for such cows, the risk of culling may be higher, all else being equal. As such, results for functional traits may be more indicative of the ability of crossbreds to delay involuntary culling, as a proxy of survival.

4.1.3 Milk production traits and somatic cell count

Regarding milk production traits, the results from this study are in agreement with Heins et al. (2008), who found that 305-d milk and protein yields in the first lactation were lower for Jersey x Holstein compared to Holstein. However, they also found that there was no difference in 305-d fat yield, whereas we found that Jersey x Holstein had a higher 305-d fat yield than Holstein. Even though McClearn et al. (2020) used total milk, fat, and protein yields, they found a similar result as in our study, where Jersey x Holstein had a lower total milk yield and a higher total fat yield. However, they did not see any difference in total protein yield when compared with Holstein. Ferris et al. (2018) also used total milk, fat, and protein yield and compared Swedish Red x (Jersey x Holstein) to Holstein and found similar results as in this study (for RxJH), namely that total milk yield and total protein yield were significantly lower and there were no differences in total fat yield (except that we found higher FAT305 in the first parity). For the Jersey crosses, the (significant) differences in the yield traits compared with the pure breeds in our study were in the range of approximately 0.2 to 1.4 SD units in both parities. Heins et al. (2008) found no difference in average somatic cell score (SCS) between Jersey x Holstein and Holstein in first lactation, whereas we found JH to have higher LSCC305 than H.

4.2 Montbéliarde crosses

4.2.1 Fertility traits

The significant improvements of fertility interval traits in parity 1 for F_1 crosses with M compared with purebred R or H were generally smaller than for crosses with J, ranging from 5 to 8 days, corresponding to 0.10–0.15 SD units. However, in parity 2, the difference in CI between MR and R was 18 days (0.31 SD units).

Our study agrees with Heins et al. (2006b), who reported a days open period that was shorter by 19 d for Montbéliarde x Holstein compared with Holstein. Hazel et al. (2020a) found that crosses between Montbéliarde and Holstein had significantly better fertility than Holstein both in the first and later lactations. They found substantially shorter days open periods of 12, 22, and 23 days for MH vs H for the first, second, and third lactations, respectively. We found smaller differences for CLI (7–8 d and 8–12 d in the first and second parity, respectively). Similarly, Hazel et al. (2020a) found much shorter days open periods for their three-breed crosses (corresponding to MxHR and RxMH) compared with H, ranging from 15 to 25 d in the first three lactations. We found shorter CLI from 6 d (n.s.) to 9–19 d (Table 4). These smaller differences might be explained by different genetic materials being used in these two studies.

4.2.2 Calving traits and survival

For Montbéliarde, there was no purebred M to compare with, however, the F_1 crosses were not better than purebred R or H for calving difficulty or stillbirths. Some of the three-breed crosses were better than one of the pure breeds, however, the difference was not consistent between the parities. For instance, RxMH had the lowest calving difficulty in parity 1, but the lowest calving difficulty in parity 2 was for MxHR, both being significantly different from H.

Heins et al. (2006a) found that Montbéliarde x Holstein had less calving difficulty in the first lactation than Holstein, but in the second lactation, there was no difference. Heins et al. (2006a) and Hazel et al. (2020b) found that Montbéliarde x Holstein had a lower stillbirth rate than Holstein in the first lactation (unlike our results) but for multiparous cows, there was no difference. Hazel et al. (2020b) found a similar result for Viking Red x (Montbéliarde x Holstein) as this study did for RxMH, namely that stillbirth was lower in the first lactation and similar for multiparous cows compared to Holstein. Their result showed that there was no difference in stillbirth between Montbéliarde x (Viking Red x Holstein) and Holstein. This disagrees with the result from this study showing that MxHR had a lower percentage of stillbirth than H (albeit not significantly so in parity 2).

Hazel et al.'s (2020b) results agree partly with the result of this study as they found that Viking Red x (Montbéliarde x Holstein) and Montbéliarde x (Viking Red x Holstein) had a higher survival to third calving compared to Holstein. They also found that Viking Red x (Montbéliarde x Holstein) had higher survival to second calving and that there was no difference between Montbéliarde x (Viking Red x Holstein) and Holstein. We found that MxHR had higher survival to lactation 2 than H, but for RxMH, the difference was not significant. Hazel et al. (2021) found that Viking Red x Holstein and Montbéliarde x Holstein had longer herd life by 96 and 219 d, respectively, compared with purebred Holstein. We found better survival to second and third calving for HR, but not for MH, compared with H.

4.2.3 Milk production traits and somatic cell count

Hazel et al. (2020a) found that compared with Holstein, Montbéliarde x Holstein had similar 305-d milk and significantly higher 305-d fat and protein yields, although the 305-d fat yield was only significantly higher in the first lactation. This was similar to our findings, although we also found significant differences for the 305-d fat yield in the second parity.

Hazel et al. (2020a) found that Montbéliarde x (Viking Red x Holstein) had significantly lower 305-d milk and fat yields in the first 3 lactations, and a lower 305-d protein yield in the first lactation compared with Holstein. Furthermore, Viking Red x (Montbéliarde x Holstein) had significantly lower 305-d milk, fat, and protein yields compared with Holstein. These results were partly similar to those from this study: in lactation 2, MxHR and RxMH had significantly lower MY305, FAT305, and PROT305. In lactation 1, it was only RxMH that had significantly lower MY305 and PROT305 but there were no differences between RxMH and H for FAT305. MxHR had a similar first lactation yield for MY305, FAT305, and PROT305 as H.

Hazel et al. (2020b) did not report SCS but found lower mastitis incidence for Montbéliarde x Holstein, Viking Red x Holstein, Montbéliarde x (Viking Red x Holstein), and Viking Red x (Montbéliarde x Holstein) in second or third (or sometimes both) parities. We found no significant differences for MH, MxHR, or RxMH compared with H.

4.3 Holstein x Swedish Red crosses

The results from the current study and those of Jönsson (2015) for HR are generally very similar, which is expected given that both studies are based partly on the same data; her data spanned the years 1990 to 2012. One difference in methodology between the two studies was that Jönsson (2015) separated Holstein x Swedish Red from Swedish Red x Holstein (sire x dam), whereas we did not. Both studies found that CI, CFI, FLI, NINS, calving difficulty, and stillbirth were significantly better for HR compared with H in the first and second lactation. Jönsson (2015) and our study also reported that HR had significantly better survival to second and third lactation compared with H.

In the first and second lactations, MY305 was significantly lower in HR than for H in both the current study and in Jönsson (2015). In our study, FAT305 was significantly higher in parity 1 and slightly but significantly lower in parity 2 for HR compared with H. Jönsson (2015) also reported these results for Swedish Red x Holstein but not for Holstein x Swedish Red. The current study showed that HR had significantly lower PROT305 than H in both parities. This also agrees with the results of Jönsson (2015) for Swedish Red x Holstein and for the second to third lactation for Holstein x Swedish Red. Both studies also found that HR had a lower somatic cell count than H. Hazel et al. (2020b) reported lower mastitis incidence for Viking Red x Holstein than for H in the third lactation but no significant difference in the first two parities.

Hazel et al. (2020a) found that Viking Red x Holstein had a lower milk yield in the first three lactations than Holstein; however, for fat and protein yields, there were no significant differences. This is similar to our results, although we obtained a higher FAT305 for HR than for H in the first lactation. They also found tendencies toward shorter days open periods, but this was only significant in parity 2. There was no difference in age at first calving in their study between HR and H. Heins et al. (2006b), however, reported a days open period that was shorter by 21 days for Scandinavian Red x Holstein than for Holstein.

Hazel et al. (2020b) described a tendency ($p < 0.1$) toward higher survival for Viking Red x Holstein crosses to second calving and significantly higher survival to third calving than for Holstein, which is similar to our results.

4.4 Heterosis

Jönsson (2015) studied crosses between Swedish Red and Swedish Holstein born between 1990 and 2012. She reported heterosis for both fertility and milk yield traits of, on average, 3%; however, for fertility traits, heterosis varied from close to zero to 12%. She found larger heterosis for calving difficulty and stillbirths (average 7.1% and 10.7%, respectively) and for survival to second and third calving (4.6% and 12.7%, respectively). For SCC, heterosis was low, around 1%. Because that study was based on data that partly overlapped with our study, the general results are also similar.

Kargo et al. (2021) estimated heterosis of approximately 4–6% for milk, fat, and protein yields for crosses between Danish Jersey (DJ) on one hand and Danish Red (DR) or Danish Holstein (DH) on the other hand. The heterosis for crosses between DR and DH was lower, approximately 3%. This is a similar pattern as in our study, both with respect to the level of heterosis and that the cross between Holstein and Red cattle resulted in lower heterosis. Their suggested explanation for this was that the genetic distance between DJ and the other breeds is larger than the genetic distance between DR and DH. A similar explanation could hold for our study.

Clasen et al. (2017) found positive heterosis for various productive life traits (time from first calving to the end of the second, third, fourth, or fifth lactation or culling) for all breed crosses (DH x DR, DH x DR, and DR x DJ) of approximately 2% to 8%. However, heterosis for time from first calving to the end of the first lactation was low and even slightly negative for crosses with DJ.

4.5 Implications and future research

Even though the rotational crossbreeding systems ProCross (Holstein, Viking Red, and Montbéliarde) and GoldenCross (Holstein, Viking Red, and Jersey) are being promoted in Sweden, there are as yet no research results showing the pros and cons of these systems for Swedish conditions. Most results from rotational crossing, especially with Montbéliarde, are based on US Holsteins and conditions. Carrying out such studies for Swedish conditions requires that there is enough data available for the relevant crosses. Hopefully, this study fills that gap, as well as presenting results that are relevant for other countries with similar conditions. However, there is a need to follow up with systems analysis studies using these results as inputs, similar to the studies done for two-breed terminal or rotational crossbreeding between Swedish Red and Holstein (Clasen et al., 2020a, b). These studies showed a consistent economic benefit of crossbreeding, however, this should also be studied for the three-breed rotational crossbreeding systems.

5 Conclusions

In general, fertility traits were improved in the F_1 crosses with J or M compared with purebred R or H (i.e., JR and MR vs. R; JH and MH vs. H), especially in the first parity. Some of the differences were not significant but they were almost always in the direction of better fertility.

Crossing R or H with Jersey resulted in lower calving difficulty than in the pure breeds in the first parity, however, in the second parity the prevalence was already so low that it was hardly noticeable and it was also not significant. However, crossing with Montbéliarde rather had a tendency to result in slightly more calving difficulties, albeit not significantly so. Generally, there was no significant change in stillbirths when crossing purebred R or H with J or M. There was a general tendency for better survival in the F_1-crosses, however, only significantly so for Jersey crosses in parity 2.

Crossing R or H with Jersey generally resulted in higher 305-d fat yield, but lower milk, ECM, and protein yields than for the corresponding pure breed (R or H). However, crossing R or H with Montbéliarde generally resulted in higher 305-d protein yields and improved (compared with R) or similar (compared with H) 305-d milk yield. For fat yield, there was an improvement for MH vs H.

As an overall summary, crossing R or H with either Jersey or Montbéliarde can be expected to result in improved fertility and probably also improved survival. Depending on the current situation in the herd, one could choose to improve fat yield (crossing with J) or protein yield (crossing with M), however, depending on the breed, there could be a trade-off, e.g., in milk yield. For other traits, one would not expect any deterioration.

Data availability statement

The data analyzed in this study is owned by the milk recording/farmers' organization and individual farmers. Requests to access these datasets should be directed to FF Freddy.Fikse@vxa.se.

Ethics statement

Ethical approval was not required for the study involving animals in accordance with the local legislation and institutional requirements because the records were collected from historical field data (routine milk recording).

Author contributions

SL: Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing. FF: Conceptualization, Data curation, Methodology, Software, Supervision, Writing – original draft, Writing – review & editing. KN: Methodology, Supervision, Writing – original draft, Writing – review & editing. ES: Conceptualization, Formal analysis, Methodology, Software, Supervision, Writing – original draft, Writing – review & editing.

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Conflict of interest

Author FF was employed by the company Växa.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

References

Clasen, J. B., Fikse, W. F., Kargo, M., Rydhmer, L., Strandberg, E., and Østergaard, S. (2020a). Economic consequences of dairy crossbreeding in conventional and organic herds in Sweden. *J. Dairy. Sci.* 103, 514–528. doi: 10.3168/jds.2019-16958

Clasen, J. B., Fikse, W. F., Kargo, M., Strandberg, E., Østergaard, S., and Rydhmer, L. (2020b). "Korsning med mjölkkor – effekter på besättningsdynamik och ekonomiskt resultat," in *Swedish [Dairy cow crosses – effects on herd dynamics and economic result] Rapporter från HGEN*. (Uppsala, Sweden: Department of Animal Breeding and Genetics, Swedish University of Agricultural Sciences). Available at: https://pub.epsilon.slu.se/17591/1/clasen_j_et_al_200924.PDF. nr 152 2020.

Clasen, J. B., Fogh, A., and Kargo, M. (2019). Differences between performance of F1 crossbreds and Holsteins at different production levels. *J. Dairy. Sci.* 102, 436–441. doi: 10.3168/jds.2018-14975

Clasen, J. B., Norberg, E., Madsen, P., Pedersen, J., and Kargo, M. (2017). Estimation of genetic parameters and heterosis for longevity in crossbred Danish dairy cattle. *J. Dairy. Sci.* 100, 6337–6342. doi: 10.3168/jds.2017-12627

DairyNZ (2021). New Zealand Dairy Statistics 2019–20. Available online at: https://www.dairynz.co.nz/publications/dairy-industry/new-zealand-dairy-statistics-2019-20/ (Accessed Mar. 16, 2021).

Dezetter, C., Bareille, N., Billon, D., Cortes, C., Lechartier, C., and Seegers, H. (2017). Changes in animal performance and profitability of Holstein dairy operations after introduction of crossbreeding with Montbéliarde, Normande, and Scandinavian Red. *J. Dairy. Sci.* 100, 8239–8264. doi: 10.3168/jds.2016-11436

Ferris, C. P., Purcell, P. J., Gordon, A. W., Larsen, T., and Vestergaard, M. (2018). Performance of Holstein and Swedish-Red × Jersey/Holstein crossbred dairy cows within low- and medium-concentrate grassland-based systems. *J. Dairy. Sci.* 101, 7258–7273. doi: 10.3168/jds.2017-14107

Hazel, A. R., Heins, B. J., and Hansen, L. B. (2017). Fertility, survival, and conformation of Montbéliarde x Holstein and Viking Red x Holstein crossbred cows compared with pure Holstein cows during first lactation in 8 commercial dairy herds. *J. Dairy. Sci.* 100, 9447–9458. doi: 10.3168/jds.2017-12824

Hazel, A. R., Heins, B. J., and Hansen, L. B. (2020a). Fertility and 305-day production of Viking Red-, Montbéliarde-, and Holstein-sired crossbred cows compared with Holstein cows during their first 3 lactations in Minnesota dairy herds. *J. Dairy. Sci.* 103, 8683–8697. doi: 10.3168/jds.2020-18196

Hazel, A. R., Heins, B. J., and Hansen, L. B. (2020b). Health treatment cost, stillbirth, survival, and conformation of Viking Red-, Montbéliarde-, and Holstein-sired crossbred cows compared with pure Holstein cows during their first 3 lactations. *J. Dairy. Sci.* 103, 10917–10939. doi: 10.3168/jds.2020-18604

Hazel, A. R., Heins, B. J., and Hansen, L. B. (2021). Herd life, lifetime production, and profitability of Viking Red-sired and Montbéliarde-sired crossbred cows compared with their Holstein herdmates. *J. Dairy. Sci.* 104, 3261–3277. doi: 10.3168/jds.2020-19137

Heins, B. J., Hansen, L. B., Hazel, A. R., Seykora, A. J., Johnson, D. G., and Linn, J. G. (2012). Short communication: Jersey × Holstein crossbreds compared with pure Holsteins for body weight, body condition score, fertility, and survival during the first three lactations. *J. Dairy. Sci.* 95, 4130–4135. doi: 10.3168/jds.2011-5077

Heins, B. J., Hansen, L. B., and Seykora, A. J. (2006a). Calving difficulty and stillbirths of pure holsteins versus crossbreds of holstein with normande, montbeliarde, and scandinavian red. *J. Dairy. Sci.* 89, 2805–2810. doi: 10.3168/jds.S0022-0302(06)72357-8

Heins, B. J., Hansen, L. B., and Seykora, A. J. (2006b). Fertility and survival of pure holsteins versus crossbreds of holstein with normande, montbeliarde, and scandinavian red. *J. Dairy. Sci.* 89, 4944–4951. doi: 10.3168/jds.S0022-0302(06)72545-0

Heins, B. J., Hansen, L. B., Seykora, A. J., Johnson, D. G., Linn, J. G., Romano, J. E., et al. (2008). Crossbreds of Jersey×Holstein compared with pure holsteins for production, fertility, and body and udder measurements during first lactation. *J. Dairy. Sci.* 91, 1270–1278. doi: 10.3168/jds.2007-0564

Jönsson, R. (2015). *Estimation of heterosis and performance of crossbred Swedish dairy cows. MSc-thesis* (Uppsala, Sweden: Department of Animal Breeding and Genetics, Swedish University of Agricultural Sciences). Available at: https://stud.epsilon.slu.se/7812/.

Kargo, M., Clasen, J. B., Nielsen, H. M., Byskov, K., and Norberg, E. (2021). Short communication: Heterosis and breed effects for milk production and udder health traits in crosses between Danish Holstein, Danish Red, and Danish Jersey. *J. Dairy. Sci.* 104, 678–682. doi: 10.3168/jds.2019-17866

McClearn, B., Delaby, L., Gilliland, T. J., Guy, C., Dineen, M., Coughlan, F., et al. (2020). An assessment of the production, reproduction, and functional traits of Holstein-Friesian, Jersey × Holstein-Friesian, and Norwegian Red × (Jersey × Holstein-Friesian) cows in pasture-based systems. *J. Dairy. Sci.* 103, 5200–5214. doi: 10.3168/jds.2019-17476

Norman, H. D., Walton, L. M., and Dürr, J. W. (2018). Reasons DHI cows exit the herd, (2018). Available online at: https://queries.uscdcb.com/publish/dhi/current/cullall.html (Accessed May 14, 2020).

R Core Team (2021). *R: A language and environment for statistical computing* (Vienna, Austria: R Foundation for Statistical Computing). Available at: https://www.R-project.org/.

SAS Institute (2013). *SAS/STAT Software, Release 9.4* (Cary, NC: SAS Institute, Inc.).

Shonka-Martin, B. N., Heins, B. J., and Hansen, L. B. (2019). Threebreed rotational crossbreds of Montb.liarde, Viking Red, and Holstein compared with Holstein cows for feed efficiency, income over feed cost, and residual feed intake. *J. Dairy. Sci.* 102, 3661–3673. doi: 10.3168/jds.2018-15682

Sjaunja, L. O., Baevre, L., Junkkarinen, L., Pedersen, J., and Setälä, J. (1990). "A Nordic proposal for an energy corrected milk (ECM) formula," in *Proceedings of the 27th Biennial Session of the International Committee for Animal Recording (ICAR)* (Pudoc, Wageningen, the Netherlands, Paris, France), 156–157.

Sorensen, M. K., Norberg, E., Pedersen, J., and Christensen, L. G. (2008). Invited review: Crossbreeding in dairy cattle: A Danish perspective. *J. Dairy. Sci.* 91, 4116–4128. doi: 10.3168/jds.2008-1273

Växa (2014). Cattle statistics. 2014. [Husdjursstatistik]. Available online at: https://www.vxa.se/statistik (Accessed 2022-01-27).

Växa (2023). Cattle statistics. 2023. [Husdjursstatistik]. Available online at: https://www.vxa.se/statistik (Accessed 2023-12-31).

VikingGenetics (2024). Available online at: https://www.vikinggenetics.com/dairy (Accessed 2024-07-05).