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Economic consequences of dairy crossbreeding in conventional and organic herds in Sweden

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ABSTRACT

This study simulated the consequences of crossbreeding between Swedish Holstein and Swedish Red on herd dynamics and herd profitability under Swedish conditions. Two base herds were simulated using a stochastic herd simulation model, SimHerd Crossbred. The herds reflected average Swedish conventional and organic herds having purebred Swedish Holstein. For each base herd, 3 breeding strategies were simulated: pure-breeding, 2-breed terminal crossbreeding, and 2-breed rotational crossbreeding. The terminal crossbreeding strategy implied having a nucleus of Swedish Holstein and a proportion of F_1 Swedish Red × Swedish Holstein crossbred cows within the same herd. The crossbreds in this herd did not produce replacement heifers but exclusively beef × dairy cross calves. Beef semen was also used in the pure-breeding (10–20% in cows) and the rotational crossbreeding (40% in cows) strategies to retain a limited surplus of replacement heifers. To ensure an adequate number of crossbreds in the terminal crossbreeding strategy, X-sorted sexed semen was used for insemination in all the purebred heifers. The outcome was 67% purebred and 31% F_1 crossbreds in the herd. In addition, 31% heterosis was expressed compared with 67% heterosis expressed using a 2-breed rotational crossbreeding strategy. Compared with the pure-breeding strategy, crossbreeding increased the annual contribution margin per cow by €20 to €59, with the rotational crossbreeding strategy creating the largest profitability. The increased profitability was mainly due to improved functional traits, especially fertility. For the conventional production system, the replacement rate was 39.3% in the pure-breeding strategy and decreased to 35.8 and 30.1% in the terminal and rotational crossbreeding strategy, respectively. Similar changes happened in the organic production system. Additionally, the crossbreeding strategies earned €22 to €42 more annually per cow from selling live calves for slaughter due to the extended use of beef semen. Milk production was similar between pure-breeding and terminal crossbreeding, and only decreased 1 to 2% in rotational crossbreeding. These results show that crossbreeding between Swedish Holstein and Swedish Red can be profitable in both conventional and organic Swedish herds using the strategies we have simulated. However, some aspects remain to be investigated, such as the economically optimal breeding strategy, genetic improvement, and transition strategies.
Key words: crossbreeding, herd management, herd profitability

INTRODUCTION

In some species of production animal, such as pigs, broilers, and beef cattle, crossbreeding at the herd level is the main breeding strategy. The crossing of parents of unrelated strains, or breeds, often results in offspring that are more robust, 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., Sørensen et al., 2008; Clasen et al., 2017; Hazel et al., 2017). Thus, the evidence from previous studies indicates that crossbreeding can deliver economic advantages for the farmer and society.

The economic benefits of crossbreeding have been previously studied. Lopez-Villalobos et al. (2000) simulated the profitability of different crossbreeding systems in New Zealand. The annual net income per cow in herds with 2- or 3-breed rotational crossbreeding Holstein with Jersey, Ayrshire, or both was NZ$6 to $28 larger than that in herds with only Holstein. In another study, Heins et al. (2012) compared Holstein cattle with Holstein × Scandinavian Red, Holstein × Montbéliarde, and Holstein × Normande in 6 US com-

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mercial herds and estimated larger projected profits of US$0.15 to $0.22 per day per animal for the crossbred cows.

Despite the compelling evidence of the benefits of crossbreeding, the majority of dairy farmers in Sweden still prefer traditional pure breeding, mainly of Swedish Red (**SR**) and Swedish Holstein (**SH**). In Sweden, crossbreeding in dairy cattle is far from common, although the proportion of crossbred dairy cows has increased slightly, with a visible upward trend since the beginning of the millennium, and is currently around 7% (Växa Sverige, 2018).

In Sweden, only a few studies to date have investigated the effects of crossbreeding between SR and SH at the animal level, and no studies have examined the impact of crossbreeding on herd profitability. Ericson et al. (1988) found almost 2% heterosis for production traits, while Jönsson (2015) found 2 to 5% heterosis for those traits. The latter study also estimated heterosis for functional traits and found 1 to 12% for fertility traits, 6 to 15% for calving traits, 5 to 13% for cow survival, and up to 35% for health traits.

The breeds considered for crossbreeding must be economically similar to make the crossbreeding system economically beneficial relative to pure-breeding (Sørensen et al., 2008). Swedish Holstein and SR were previously estimated to be at the same economic level (Stålhammer, 2014), although the former provide higher income from milk yield and the latter incur lower costs related to health and other functional traits. In other words, the 2 breeds complement the strengths and weaknesses of each other and are therefore potentially suited for use in a crossbreeding system.

The reluctance of Swedish farmers to use crossbreeding as a strategy in their herds may be due to their lack of knowledge of the economic gains. The aims of this study were to simulate the outcomes for herd dynamics and profitability when terminal or rotational crossbreeding strategies with SH × SR are implemented and to compare these outcomes with those for pure-breeding with SH. We hypothesized that crossbreeding between the 2 breeds would generate economic gain in both organic and conventional Swedish herds.

MATERIALS AND METHODS

In this simulation study, we used the SimHerd model, which has been applied in several studies of dairy herd management (e.g., Sørensen and Østergaard, 2003; Nielsen et al., 2006; Ettema et al., 2017). To simulate crossbreeding, we used a modification (SimHerd Crossbred) to account for breed proportion and heterozygosity in each individual animal and to simulate phenotypic breed effects and heterosis effects. This approach allows for the simulation of different crossbreeding systems at the herd level (Østergaard et al., 2018).

In SimHerd, the state of an animal is defined by its age, lactation stage, milk yield (actual and potential), body weight, stage in estrus cycle, pregnancy stage, somatic cell count, disease status, and culling status. The SimHerd model predicts consequences of given changes in biology and management in a dairy herd by stochastic simulation of state changes at the animal and herd levels. From one week to the next, an animal's state may change. Relevant probabilities trigger discrete events (e.g., disease, heat detection, abortion, conception, death, and culling). The state of all the animals in the herd defines the state of the herd including the herd demography (Østergaard et al., 2010). Several input parameters act as decision variables that control herd dynamics, baseline risks of diseases, heat observation rate, culling strategy production level, fertility, and health. Outputs of the SimHerd model in terms of technical herd figures can be used to make economic calculations.

Scenarios

Two base herds were specified to reflect average Swedish organic and conventional herds with purebred SH. For each base herd, we simulated 3 breeding strategies—pure-breeding, 2-breed terminal crossbreeding, and 2-breed rotational crossbreeding (Figure 1, and described later)—in a total of 6 scenarios. The simulated herd size was approximately 100 cows. Average herd size in Sweden is currently around 90 cows, but it is increasing (Växa Sverige, 2018). We simulated the scenarios for 50 yr to ensure that an equilibrium was reached; for most scenarios, the equilibrium was reached at approximately yr 20 of the simulation. The results shown in this study are averages of 1,000 replicates over the last 10 yr at equilibrium.

Breed Differences and Heterosis Estimates

Phenotypic breed differences (Table 1) were specified as input parameters in the SimHerd Crossbred model for production, risk of diseases, fertility, and mortality. We based the input parameters on raw means drawn from data collected from the Swedish cattle database (organized by Växa Sverige, Uppsala, Sweden) on cows that had a calving event between 2011 and 2016. The data set consisted of milk recording data from 41,275 organic and 687,828 conventional SH cows and 35,860 organic and 440,924 conventional SR cows.

The heterosis effects for F_1 crossbreds used in the model are all favorable (see Table 2). They are based on findings from Jönsson (2015) and a review by Sørensen

Table 1. Phenotypic breed differences of Swedish Red relative to Swedish Holstein as input parameters in the model for production, risk of diseases, fertility, and mortality[1]

Item	Unit	Conventional	Organic
305-d kg of ECM, first parity	Relative ratio	0.95	0.95
305-d kg of ECM, second parity	Relative ratio	0.91	0.91
305-d kg of ECM, third parity	Relative ratio	0.90	0.89
Feed conversion efficiency	Additive change	0.00	0.00
Mastitis	Odds ratio	0.74	0.86
Milk fever	Odds ratio	1.00	0.80
Retained placenta	Odds ratio	1.00	0.81
Metritis	Odds ratio	0.60	0.60
Displaced abomasum	Odds ratio	0.60	0.44
Ketosis	Odds ratio	1.00	1.58
Digital dermatitis	Odds ratio	0.80	0.97
Interdigital hyperplasia	Odds ratio	0.84	0.96
Hoof horn diseases	Odds ratio	0.62	0.75
Dystocia	Odds ratio	0.81	0.88
Cow mortality	Odds ratio	0.55	0.55
Calf mortality within 24 h	Odds ratio	0.59	0.74
Calf mortality after 24 h	Odds ratio	1.08	1.11
Insemination rate, heifers	Odds ratio	1.00	1.00
Insemination rate, cows	Odds ratio	1.23	1.23
Conception rate, heifers	Odds ratio	1.00	1.00
Conception rate, cows	Odds ratio	1.52	1.52
Calving—first AI, cows	Additional, days	−3	−9

[1]Values are calculated from data obtained from the Swedish cattle database (organized by Växa Sverige, Uppsala, Sweden).

et al. (2008). In a departure from the original SimHerd model, the effect of diseases on reproduction and milk yield was turned off in SimHerd Crossbred to prevent double counting from the combined effect of heterosis on milk yield and diseases. In other words, the heterosis effects on milk yield and reproduction parameters already include effects of diseases; therefore, the direct effect of a disease on those parameters was reset. For the

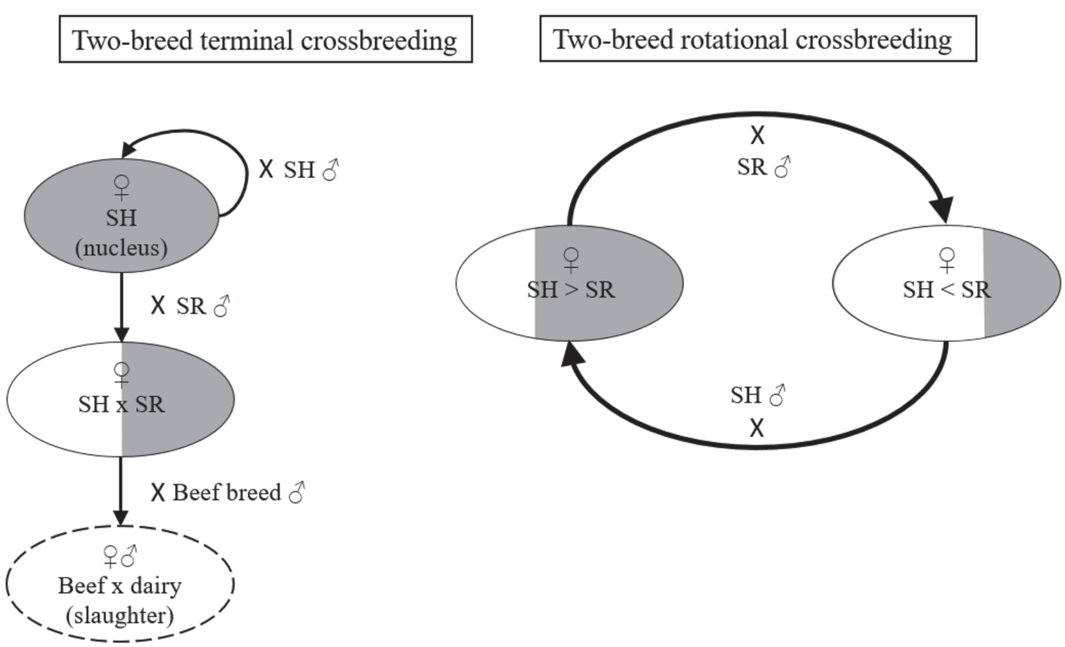

Figure 1. Illustration of 2-breed terminal crossbreeding (left) and 2-breed rotational crossbreeding (right). Terminal crossbreeding requires a nucleus of purebred Swedish Holstein (SH), with some of the females being bred to a sire of the same breed to maintain the size of the nucleus. The remainder of the SH females are bred to a Swedish Red (SR) sire to produce F_1 crossbred production cows. The crossbred SR × SH females are mated to a sire of a beef breed, and all resulting offspring are for meat production only. In rotational crossbreeding, females are rotated between the 2 sire breeds in each generation. Females with a larger proportion of SH than SR are bred to an SR sire and vice versa.

base herd scenarios with a pure-breeding strategy, the general risks of diseases were adjusted so the simulated result continuously reflected the herds we wanted to simulate, as if we had used the original SimHerd model.

SimHerd Crossbred does not model breeding values or genetic change. Therefore, the traits for each individual animal were sampled randomly based on the phenotypic mean of the animals in the herd, which was based on the phenotypic parameters specified in the initial herd and a phenotypic standard deviation. Effect of breed and heterosis were added in accordance with the animal's breed composition and degree of heterozygosity, as described by (Østergaard et al., 2018).

Aside from phenotypic differences between the animals, the 2 production systems differed with respect to 2 management procedures: milk withdrawal period and milk feeding of newborn calves. The milk withdrawal period after medical treatments was twice as long in the organic production system as in the conventional system. Calves in the conventional production system were fed milk replacer, whereas those in organic production were fed bulk tank milk in accordance with KRAV-label regulations (KRAV, 2017).

Breeding Strategies and Reproduction

In the simulations, 2-breed terminal crossbreeding was implemented within a herd, meaning that 2 groups of animals were used for milk production in the herd: a purebred "nucleus" consisting of SH and a group of F_1 SR × SH crossbreds (Figure 1). Terminal crossbreeding with 2 breeds indicates that only purebred animals are selected for the production of replacement heifers, and those females produce both purebred and crossbred replacement heifers. Therefore, all crossbred animals in this system will express 100% heterosis, and they will produce only beef × dairy cross calves.

A 2-breed rotational crossbreeding system implies that females are mated to sires of the breed of the maternal grandsire, and that the breed of the sire therefore "rotates" for each female generation (Figure 1). Approximately 5 generations after the implementation of this system in a purebred herd, individual animals in the herd will constitute of 67% SH or SR and 33% of the other breed. At equilibrium, 67% of the F_1 heterozygosity is expressed in all animals in the herd.

Initially, all females in herds with pure-breeding and rotational crossbreeding were serviced with conventional semen (**CS**). Any purebred virgin heifer in the herds with terminal crossbreeding was serviced with sexed semen (**SS**) to ensure adequate numbers of replacement heifers. To reflect common practice in Swedish dairy herds, 2 attempts were made to impregnate the heifers with SS, and if the attempts were unsuccessful, the heifers were serviced with CS. All purebred cows were serviced with CS. All crossbred females in the herds with terminal crossbreeding were serviced with beef semen (**BS**). It was assumed that all beef × dairy calves would be sold for slaughter finishing in another herd.

The rate of heat observation expressed a combination of the probability of observing heat (by eyesight or heat detection technology) and the cow's ability to show heat signs. Conception rate was defined as the number of positive pregnancy tests over all inseminations. Pregnancy tests were conducted 5 wk after insemination unless heat was observed again before that time point. Initial herd input parameters for chance of conception were 40% for cows and 62.5% for heifers, and the probability of heat observation was 35% for cows and 65% for heifers, corresponding to SH figures obtained from the Swedish cattle database. The 2 production systems did not differ for these 2 parameters. The relative conception probability of SS was 0.85 compared with CS, and the probability of a female calf using SS was 0.90 compared with 0.48 with CS.

Culling Decisions

The model sought to maintain a herd size of between 100 and 105 cows, but it only replaced cows that died or were culled involuntarily (due to disease) or voluntarily (due to infertility or low milk yield). In case no spots were available for a calving-ready replacement heifer, it was sold as a pregnant heifer. In cases in which no calving-ready replacement heifers were available to take an open spot, the model purchased a pregnant heifer from another "fictive" herd.

Cows were voluntarily culled if they produced less milk than average, or if they were unable to become pregnant within a certain period between the voluntary

Table 2. Assumed heterosis estimates for F_1 Swedish Red × Swedish Holstein, based on estimates from Jönsson (2015) and Sørensen et al. (2008)

Trait	Heterosis (%)
305-d kg ECM	3
Mastitis	10
Other diseases[1]	10
Dystocia	7
Fertility	10
Cow mortality	10
Calf mortality and stillbirth	12
Young stock mortality	12

[1]Retained placenta, metritis, milk fever, displaced abomasum, ketosis, digital dermatitis, interdigital hyperplasia, sole ulcers, heel horn erosion, and hock lesions.

waiting period and maximum number of days open. The parameters for these periods differed between production systems and were based on data retrieved from the Swedish cattle database. The cows were inseminated 49 to 324 d after calving in conventional herds and 51 to 331 d after calving in organic herds, regardless of parity number.

Heifers were voluntarily culled if they were unable to become pregnant within the minimum age at first insemination and maximum number of days open. They were inseminated between 470 and 810 d of age in the conventional production system and between 470 and 770 d of age in the organic production system.

Dairy bull calves and beef × dairy bull and heifer calves were sold for slaughter production after a 2-wk rearing period. Dairy heifers reared to become production cows were the only young stock on the farm, and any economic results relating exclusively to young stock accounted for this group of animals.

Health and Mortality

The simulated outcome of disease prevalence was defined as the number of treatments for specific diseases. This number included both first and follow-up treatments each time a cow needed veterinary treatment for a specific disease. In the presentation of results, we pool the simulated diseases into 5 groups: mastitis, hoof and leg diseases, metabolic diseases, reproduction diseases, and dystocia (i.e., calving difficulties requiring veterinary assistance). Mastitis and dystocia only included those specific disorders. Hoof and leg diseases included digital dermatitis, interdigital hyperplasia, sole ulcers, heel horn erosion, and hock lesions. Metabolic diseases included milk fever, displaced abomasum, and ketosis, and reproduction diseases included metritis and retained placenta. The risk of any disease was consistent between production systems but differed between parities and changed during the lactation period (Østergaard et al., 2000). Furthermore, each disease was associated with a risk of involuntary culling.

We defined cow mortality as the proportion of cows that died or were euthanized in response to acute conditions. Calf mortality relates to calves dying within 24 h of calving, including stillbirth. The relative risk of stillbirth when BS was used as compared with dairy bull semen (CS or SS) was 1.05, irrespective of the age of the mother. Young stock mortality included replacement heifers that died between 24 h after birth and first calving. The risk of young stock mortality decreased with the age of the heifer. Replacement rate expressed the annual number of replacement heifers entering the cow herd divided by the number of cow years.

Calibration of Simulations

Before the final simulation, we ran test simulations to ensure the output parameters were reasonable in relation to the input parameters and to make appropriate breeding decisions for the simulated herds.

We decided to retain a surplus of 1 to 3 replacement heifers in each scenario to make the scenarios economically comparable. A large difference in surplus heifers will make any other economic effect vanish in relation to the high value of buying or selling replacement heifers. With the initial breeding decisions described earlier, the herds managing pure-breeding or rotational crossbreeding had a surplus of replacement heifers above 3, and we therefore calibrated sufficient proportions of BS into these scenarios. We continued to service the remaining females in these herds with CS. The calibrated proportions of BS used in these scenarios are presented in the results.

In the terminal crossbreeding strategy, the nucleus of purebred animals had to be maintained at an appropriate size to produce a sufficient amount of purebred and crossbred replacement heifers. When all the purebred females were serviced with CS, the breeding strategy resulted in only 5% crossbred cows in the herd. Adhering to our original decision that all purebred heifers should receive SS, this proportion increased to about 30% crossbreds, which is more substantial. After this calibration step, 75% of all purebred females across age groups were bred to an SH sire for pure-breeding and 25% were bred to an SR sire for crossbreeding. The cows were selected randomly for pure-breeding or crossbreeding, because the SimHerd Crossbred model does not simulate breeding values. The distribution of surplus purebred and crossbred heifers reflected the simulated distribution of purebred and crossbred production cows.

Price Assumptions

The annual contribution margin (**CM**) included income from milk production, slaughter cows, live calves, and surplus replacement heifers, and the costs of feeding the cows and replacement heifers, inseminations (including the service fee), disease treatments, and other costs related to the rearing of the cows and replacement heifers (e.g., bedding, hoof trimming, vaccinations). Labor costs and costs associated with buildings, farming equipment, and other investments were not included.

The price and cost assumptions made in the simulations were based on budgets from Agriwise (2017) and price lists from Växa Sverige (2017), Arla (2017), and HKScan Agri (2017). Essential price and cost assumptions in euros are given in Table 3. Milk and meat were of greater value in organic production, but this production system was also associated with greater feed costs. The ECM produced by crossbreds was assumed to be slightly more valuable as a result of its higher fat and protein content in SR relative to SH (Växa Sverige, 2018). Surplus heifers were sold as pregnant heifers and purebred heifers were assumed more valuable than crossbreds because they would potentially have estimated breeding values. Breeding values for crossbred dairy cattle in Sweden were not estimated at the time of this study. Additionally, heifers pregnant with SS were assumed to be worth 5% more (not shown in Table 3) because of the higher chance of a heifer calf that can be used in future as a replacement heifer.

The slaughter value was assumed to be €0.05/kg live weight higher for an SR cow than an SH cow, due to higher carcass scores (Gård and Djurhälsan, 2018). The benefit was regressed with breed proportion. Thus, a conventional F_1 SR × SH crossbred cow would have a value of €1.325/kg live weight. Likewise, a live calf sold for slaughter was assumed to be more valuable if it was a SR × SH crossbred, as compared with a purebred SH, because SR calves have a faster growth rate and better carcass quality (Gård and Djurhälsan, 2018). In addition, dairy × beef crossbreds were of higher value as a result of the larger growth potential owing to the beef breed genes. The prices for live calves included costs expected to be incurred in a 2-wk rearing period and were adjusted in line with a 3% risk of mortality within that period.

Costs of disease treatments (not shown in Table 3) were based on the price sheet used in Nordic Total Merit Index calculations (Sørensen et al., 2018) and included expenditures on medicine and veterinary fees. In the organic production system, a veterinarian must undertake all the requisite treatments for most diseases. By contrast, farm personnel are permitted to do follow-up treatments for most diseases in the conventional production system. Therefore, the costs were assumed higher for most diseases in the organic production system. Thus, a case of mastitis was taken to cost €125 in a conventional herd and additional €50 in an organic herd, and for hoof and leg diseases, the cost ranged between €15 and €60 plus up to an additional €30 in the organic system. Costs of remaining diseases were between €90 and €225 plus up to an additional €50 in the organic system.

Sensitivity Analyses

Three different sensitivity analyses were carried out to investigate the effect of some of the potentially important assumptions. The sensitivity analyses were only made for the conventional production system, assuming patterns would be the same in both production systems. The first sensitivity analysis investigated the effect of the breed difference in milk yield on CM by changing the relative ratio in SR versus SH to 1.00, 0.975, 0.95, 0.925, 0.90, 0.875, and 0.85, regardless of lactation number. The second sensitivity analysis investigated changes in milk price relative to the current simulated milk price (€372/1,000 kg of ECM) between −20% and +20%. The third sensitivity analysis investigated changes in all feedstuff prices relative to the current (shown in Table 3) between −20% and +20%. All other prices were kept constant for the second and third analyses, including the breed difference in milk price.

Table 3. Assumed income prices and costs for milk production, feeding, slaughter, live animals, and semen services; addition for Swedish Red (compared with Swedish Holstein) in parentheses

Item	Conventional (€)	Organic (€)	Source
Income			
Milk, per 1,000 kg of ECM	372 (+4)	481 (+4)	Arla (2017)
Slaughter cow, per kg of live weight	1.30 (+0.05)	1.34 (+0.05)	HKScan Agri (2017)
Purebred pregnant heifer, per head	1,220	1,220	Agriwise (2017)
Crossbred pregnant heifer, per head	1,100	1,100	—
Dairy bull calf, per head	200 (+25)	200 (+25)	HKScan Agri (2017)
Beef × dairy bull calf, addition per head	70	70	HKScan Agri (2017)
Beef × dairy heifer calf, addition per head	35	35	HKScan Agri (2017)
Costs			
TMR, cows, per kg DM[1]	0.19	0.22	Agriwise (2017)
Concentrate, young stock, per kg of DM	0.27	0.46	Agriwise (2017)
Roughage, young stock, per kg of DM	0.12	0.12	Agriwise (2017)
Conventional semen (including service)	34	34	Växa Sverige (2017)
Sexed semen (including service)	39	39	Växa Sverige (2017)
Beef semen (including service)	34	34	Växa Sverige (2017)

[1]Includes 90 d on pasture with additional TMR feeding.

RESULTS

Herd Dynamics

All simulated herds had 103 cows per year on average during the 10-yr period presented in the results shown in Table 4. As a result of the breeding strategy, the terminal crossbreeding scenarios had 31% crossbred cows and 69% purebred cows, regardless of production system. Given that all crossbreds were 50/50 of each breed, the average breed proportions in the herds were calculated as 84.5% SH (0.31 × 0.5 + 0.69) and 15.5% SR (0.31 × 0.5). In addition, 31% heterosis was expressed across the herds in terminal crossbreeding scenarios. For rotational crossbreeding, the average proportion of each breed was 50%, and because all animals were crossbreds, 67% heterosis was expressed across the herds in these scenarios.

Changing from pure-breeding to crossbreeding led to a decrease in the number of young stock animals in both production systems; the replacement rate was reduced as well due to decreased voluntary culling. The largest effect for both production systems was in the rotational crossbreeding scenarios. Furthermore, crossbreeding altered the age structure among the cows: the proportion of third-parity and older cows in the herd increased.

The crossbreeding strategies allowed for more use of BS as a result of the better reproductive performance of the crossbreds relative to purebreds, and therefore more beef × dairy cross calves were born in these scenarios. In the pure-breeding scenarios, 17% (organic) and 12% (conventional) of all calves sold were beef × dairy crosses. The corresponding proportions were 53 and 54% in terminal crossbreeding and 43% in both rotational crossbreeding scenarios.

Animal Performance

In both production systems, the level of 305-d ECM yield in the pure-breeding and terminal crossbreeding scenarios was similar. In the rotational crossbreeding scenarios, minor reductions occurred in milk yield (115–184 kg, corresponding to 1–2%) as compared with the yield in the pure-breeding scenario. The average daily yield per cow between wk 1 and 24 after calving (not shown in table) in the conventional production system was 28.9 kg of ECM in first-parity cows for both pure-breeding and terminal crossbreeding and 28.7 kg of ECM for rotational crossbreeding. In multiparous cows, it was 38.8, 38.6, and 37.9 kg of ECM for pure-breeding, terminal, and rotational crossbreeding, respectively. The corresponding average daily yield per

Table 4. Simulated herd dynamics at equilibrium in a herd of purebred Swedish Holstein; a herd using a 2-breed terminal crossbreeding system with Swedish Holstein purebreds and F_1 Swedish Red × Swedish Holstein crossbreds; and a herd using 2-breed rotational crossbreeding—all simulations in both organic and conventional production systems

	Organic			Conventional		
Item	Purebred	Terminal	Rotation	Purebred	Terminal	Rotation
Cows (no.)	103	103	103	103	103	103
Crossbred cows (%)	0	31	100	0	31	100
First-parity cows (%)	39	36	30	39	36	30
Second-parity cows (%)	24	23	21	24	23	21
Older cows (%)	37	41	49	37	41	49
Replacement (%)	38.2	36.4	30.3	39.3	35.8	30.1
Young stock (no.)	90	88	73	93	84	72
Surplus heifers sold (no.)	1	2	2	1	1	2
Sexed semen doses, heifers (%)	0	60	0	0	60	0
Beef semen doses, heifers (%)	0	21	0	0	21	0
Beef semen doses, cows (%)	15	30	40	10	30	40
Dairy bull calves sold (no.)	45	27	37	46	26	37
Beef × dairy crosses sold (no.)	9	31	28	6	30	28
305-d ECM yield (kg)	9,148	9,178	9,033	10,007	9,969	9,823
Calving interval (d)	415	409	401	409	406	400
Conception rate (cows)	0.36	0.38	0.43	0.36	0.39	0.43
Mastitis treatments/100 cows	11.5	11.9	12.1	9.7	9.7	9.4
Hoof and leg disease treatments/100 cows	19.2	19.2	18.7	21.7	20.4	18.4
Metabolic disease treatments/100 cows	2.5	2.6	2.6	1.4	1.4	1.4
Reproduction disease treatments/100 cows	5.0	4.8	4.0	1.6	1.5	1.3
Dystocia cases/100 cows	3.7	3.5	3.0	5.9	5.4	4.4
Total disease treatments/100 cows	41.9	42.0	40.4	40.3	38.4	34.9
Cow mortality (%)	6.3	5.7	4.7	6.3	5.8	4.5
Calf mortality (%)	5.8	5.3	4.7	8.6	7.7	6.3
Young stock mortality (%)	3.6	3.5	3.4	3.6	3.5	3.5

cow in the organic production system was approximately 3 kg of ECM less, with more or less the same differences between breeding scenarios, relative to the conventional production system.

Crossbreeding improved fertility in comparison with pure-breeding. The calving interval was shorter and the conception rates were higher in both production systems. The largest effect was in the rotational crossbreeding scenarios.

Hoof and leg diseases accounted for about half of the disease treatments, and mastitis accounted for about a quarter. These rates were followed by low prevalences of reproduction diseases, dystocia, and metabolic diseases. In the organic production system, the number of mastitis treatments per 100 cows slightly increased when crossbreeding was introduced, but it remained at a similar level in the conventional production system. In both production systems, the number of treatments for hoof and leg diseases declined when crossbreeding was implemented. Reproduction diseases and dystocia also declined slightly with the change from pure-breeding to crossbreeding. The number of treatments of metabolic diseases remained virtually unaffected with the change from pure-breeding to crossbreeding.

Total numbers of treatments (including dystocia) per 100 cows in pure-breeding and terminal crossbreeding in the organic production system were similar, but they decreased by 4% in rotational crossbreeding. In the conventional production system, total disease frequency decreased by 5% in the terminal crossbreeding scenario and by 9% in the rotational crossbreeding scenario.

Crossbreeding had a favorable effect on survival rates in the herds. In both production systems, cow mortality fell when the breeding strategy changed from pure-breeding to crossbreeding. Calf mortality (including stillbirths) decreased as well. Regardless of production system, the mortality rate in young stock only decreased (and then only slightly) when crossbreeding was implemented.

Economic Output

Total annual CM in the organic production system increased by 1.9% (€51) and 2.2% (€59) in the terminal and rotational crossbreeding scenarios, respectively, as compared with pure-breeding. In the conventional production system, the corresponding increases were 0.9% (€20) and 1.7% (€39).

More than 90% of the income in all simulated herds derived from milk production; the remaining income came from the sale or slaughter of animals. A 1% increase in annual income per cow from milk production occurred when pure-breeding was replaced by terminal crossbreeding in the organic production system (Table 5). In the rotational crossbreeding scenario, a loss of 1% occurred. In the conventional production system, the losses were 1% for terminal crossbreeding and 2% for rotational crossbreeding. Because of the reduced replacement rate in the crossbreeding scenarios, fewer cows were slaughtered every year, reducing the income from slaughter cows as well. However, a larger proportion of beef × dairy cross calves increased the income from live calves by 20 to 40% (€22–€42), regardless of production system. In the organic production system, the proportional difference between the pure-breeding and crossbreeding scenarios in total annual income per cow was similar to that observed in connection with milk income. In the conventional production system, the total incomes in pure-breeding and terminal crossbreeding were the same, but total income was 1% lower in the rotational crossbreeding scenario.

Most annual costs are feeding costs. Regardless of production system, the feeding costs for the cows were similar in pure-breeding and terminal crossbreeding and 1% less in rotational crossbreeding. The reduced number of replacement heifers saved 3 to 23% of the feed costs and other costs related to young stock. Total costs fell by 4% in the rotational crossbreeding strategy in the organic production system and by 2 to 6% in all crossbreeding strategies in the conventional production system.

Sensitivity Analyses

With a decrease in the relative ratio in 305-d kg ECM yield between SR and SH (increased difference for production performance of SR relative to SH), the CM in the crossbreeding scenarios decreased as well (Figure 2). Between a relative ratio of 1.00 and 0.85, the effect of rotational crossbreeding on CM decreased from +4.7% to −4.1% relative to pure-breeding, while the corresponding effect in the terminal crossbreeding system was from +1.6% to −0.1%.

The relative CM between the pure-breeding scenario and the crossbreeding scenarios increased up to +1.7% for terminal and +3.3% for rotational crossbreeding at 20% reduction in milk price (Figure 3). Increasing the milk price by 20% caused CM to be less favorable for crossbreeding, but it still remained positive at +0.6% and +0.8% for terminal and rotational crossbreeding, respectively.

Changes in feed prices showed an almost opposite trend from changes in milk price (Figure 4). When the feed price was reduced by 20%, the relative CM between the pure-breeding scenario and the crossbreeding scenarios was +0.7% and +0.9% for terminal and ro-

Table 5. Simulated annual economic consequences (€/cow) in a herd of purebred Swedish Holstein; a herd using a 2-breed terminal crossbreeding system with Swedish Holstein purebreds and F_1 Swedish Red × Swedish Holstein crossbreds; and a herd using 2-breed rotational crossbreeding—all simulations in both organic and conventional production systems

	Organic			Conventional		
Item	Purebred	Terminal	Rotation	Purebred	Terminal	Rotation
Income						
Milk sales	4,360	4,383	4,323	3,730	3,694	3,652
Slaughter cows	269	259	218	270	248	214
Live calves	109	131	150	104	127	146
Surplus heifers	12	26	26	16	16	20
Total	4,751	4,798	4,717	4,093	4,085	4,033
Costs						
Feeding, cows	1,442	1,446	1,431	1,245	1,242	1,230
Feeding, young stock	345	336	281	250	226	192
Inseminations	50	53	46	51	52	45
Disease treatments	55	55	53	35	34	30
Other, cows	142	142	140	144	142	140
Other, young stock	54	52	43	55	50	43
Total	2,078	2,073	1,985	1,780	1,747	1,681
Total contribution margin[1]	2,674	2,725 (+1.9%[2])	2,733 (+2.2%)	2,313	2,333 (+0.9%)	2,352 (+1.7%)

[1]Total economic values are not exactly sums of the subvalues due to rounding of each subvalue.

[2]Percentage increase from the pure-breeding scenario within the same production system.

tational crossbreeding, respectively. The corresponding figures were +1.4% and +2.6% when then feed prices were increased by 20%.

DISCUSSION

To our knowledge, very few studies have investigated crossbreeding performance at the herd level for specific crossbreeding systems and production systems. Indeed, most studies on crossbred performance are on F_1 crosses and conducted at the animal level rather than the herd level. In 2 different production systems in Sweden, organic and conventional, the simulations in the current study showed that improvements in cow replacement rate and profitability especially were secured through a switch from a pure-breeding to crossbreeding strategy in a dairy herd. The results may not directly apply to a specific Swedish herd or a herd from another country because herd parameters, management strategies, and breeds differ within and between countries.

Despite minor reductions in milk yield, which is by far the largest income factor in current dairy production, improved functional traits were key to economic improvement. Beyond that, improved health and reduced mortality were important welfare parameters. This result may ultimately be as important as economic output, because animal welfare and longevity are serious

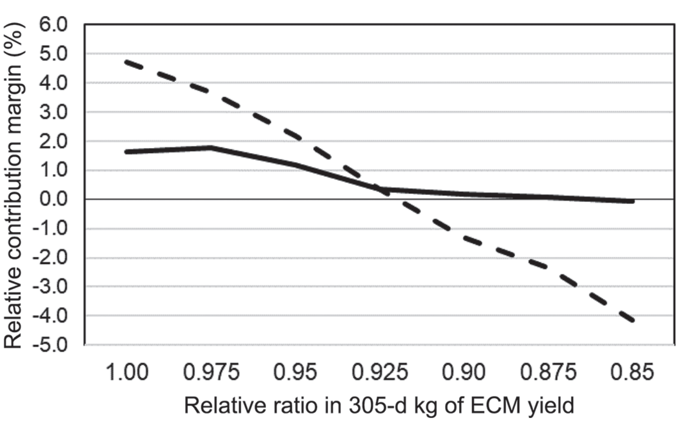

Figure 2. Relative contribution margin between pure-breeding with Swedish Holstein and terminal crossbreeding (solid line) or rotational crossbreeding (dashed line) between Swedish Red and Swedish Holstein when the relative ratio in 305-d kg of ECM yield changes between the 2 breeds.

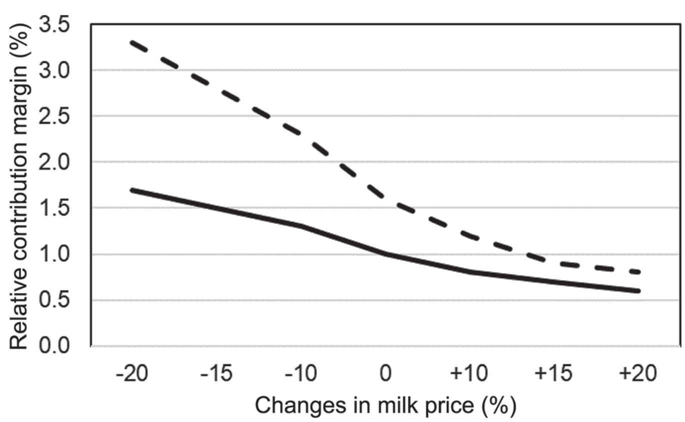

Figure 3. Relative contribution margin between pure-breeding with Swedish Holstein and terminal crossbreeding (solid line) or rotational crossbreeding (dashed line) between Swedish Red and Swedish Holstein when milk price is changed between −20% and +20%.

concerns among Swedish dairy farmers (Röcklinsberg et al., 2016).

The data used as input parameters in our simulations were averages from the whole country. They did not reflect the influence of interactions between, for example, production system and geographical location. These interactions may influence the breed differences used. Some differences are thought to exist between dairy herds in the north of Sweden and those in the south—differences that may be due to herd size and roughage production, as well as the fact that organic production is more common in some regions than others (Jordbruksverket, 2017; Växa Sverige, 2018).

Herd Dynamics

The effect of crossbreeding was strongly expressed in the fertility parameters. This outcome was especially noticeable in the terminal crossbreeding scenarios, in which the crossbred cows managed to improve the overall conception rate and calving interval in the herd, although only 31% of the cows were crossbreds.

When crossbreeding was introduced in the purebred herd, the improved functional traits reduced the number of replacement heifers needed in the herd. Reduction of young stock is favorable because it leads to lower costs in feeding and rearing and may also have other benefits, such as reducing the environmental impact of dairy production (Ondersteijn et al., 2003). Furthermore, costs for labor and the housing of heifers are lower, although this cost effect was not included in the economic results presented here. Reducing the number of young stock animals may allow for an increased number of production cows and thus increase economic gains as well. From an environmental perspective, Ettema et al. (2017) has calculated that a reduction of 32 replacement heifers in a Danish system led to a potential increase of 8.5 production cows with no increase in the number of methane-producing equivalents. However, from either a practical or logistic point of view or both, increasing the number of production cows may not be possible in all herds or production systems.

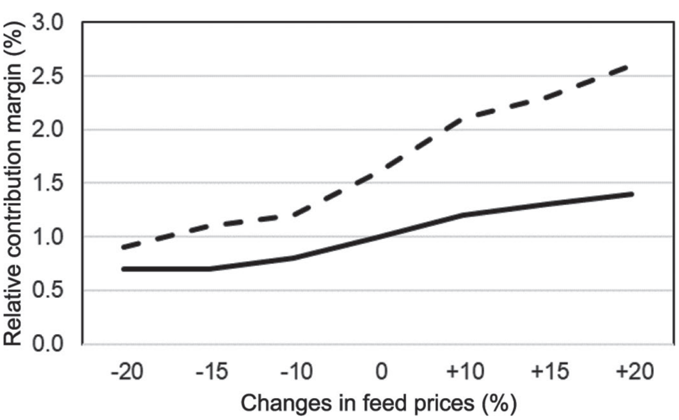

Figure 4. Relative contribution margin between pure-breeding with Swedish Holstein and terminal crossbreeding (solid line) or rotational crossbreeding (dashed line) between Swedish Red and Swedish Holstein when feed prices are changed between −20% and +20%.

A terminal crossbreeding system relies on the provision of enough replacement heifers, both purebreds and crossbreds, which is entirely dependent on an optimal proportion of purebreds. In general, the proportion of purebred animals needed is highly dependent on fertility. Improved fertility allows for smaller nucleus size (i.e., more crossbred animals in the herd), mainly because the calving interval decreases and fewer cows are culled voluntarily in response to infertility. Reduced cow and heifer mortality (including stillbirths) allows for a smaller nucleus size as well. Additionally, the 31% of crossbreds in our simulations can be increased by a different strategy for using SS.

A terminal crossbreeding strategy requires SS to be used to reach an adequate number of crossbreds in the herd to achieve the benefits of crossbreeding. In our simulations, we chose to limit the use of SS to heifers only, which allowed 75% pure-breeding in the nucleus resulting in a nucleus size of 69% purebred cows. But the nucleus size in terminal crossbreeding can be reduced further if SS is used in cows as well. Moreover, using SS at the herd level on the genetically best heifers and cows can increase genetic levels in the purebred cows (Hjortø et al., 2015; Ettema et al., 2017), and this outcome will be reflected in the crossbreds as well. However, the economic value of the increased genetic gain obtained by using SS was not included in the results presented in this study. Sexed semen should not necessarily be limited to pure-breeding; it may benefit crossbreeding as well. We did not investigate the economically optimum proportion of purebreds versus crossbreds in a terminal crossbreeding system, but it may vary with the level of management in the herd and the performance of the purebreds (Clasen et al., 2019).

Sexed semen was not used in the rotational crossbreeding scenarios in this study, but this crossbreeding strategy would also benefit from the use of SS because that would allow for increased use of BS. This approach may improve profitability, because BS increases the average value of slaughter calves. Meat production from beef × dairy crosses may have a smaller environmental impact than production from suckler cow herds (Cederberg and Mattsson, 2000). The combination of BS and SS potentially increases the rate of genetic improvement in the herd (Ettema et al., 2017), although that demands selection tools for crossbred animals, such as breeding values (discussed further in the section about breeding).

Production

Milk yield was expected to decrease when crossbreeding was introduced to a purebred herd, because it is lower in SR than it is in SH. However, the combination of heterosis for milk yield and the larger proportion of older cows in the herd created only a minor reduction in milk yield when rotational crossbreeding was introduced. The relatively low proportion of SR in terminal crossbreeding caused the milk production level to change even less.

Relative to pure-breeding, the average daily kilograms of ECM yield per cow between wk 1 and 24 was, across lactations, ~0.3% less in the terminal crossbreeding scenarios and ~1.5% less in the rotational crossbreeding scenarios. For F_1 crossbreds between SR and SH, Jönsson (2015) estimated an average difference in milk production across 3 lactations. Relative to purebred SH, the crossbreds produced on average 4.6% less 305-d kg ECM. In the United States, Hazel et al. (2017) measured production traits in first-parity Viking Red × Holstein crosses versus purebred Holstein. When converting 305-d milk volume and fat and protein contents to 305-d ECM, they showed just a 0.5% difference in favor of the purebreds. Clasen et al. (2019), however, found no significant ($P > 0.05$) difference in 305-d kg fat plus protein yield between first-parity purebred Holstein and Nordic Red × Holstein crosses.

A comparison between previous studies from Jönsson (2015), Hazel et al. (2017), and Clasen et al. (2019) and the present study is less than straightforward because studies on F_1 crossbred animals do not represent the effects at the herd level, but rather at the animal level, and fail to take herd demography into account. For example, differences in age distribution among production cows between a purebred and crossbred herd are not reflected in those estimates. Furthermore, only 67% heterosis is expressed in rotational crossbred animals, whereas it is fully expressed in F_1 crossbreds. Because SimHerd Crossbred was not programmed to output performances for breed groups (i.e., purebreds and F_1 crossbreds separately) and instead gave performances for the entire herd, comparisons of F_1 crossbreds from our simulated terminal crossbreeding system and studies of F_1 crosses were also impossible.

Health and Survival

The prevalence of most diseases was very low because of the low mean values extracted from the Swedish cattle database that were used as input parameters. Because of the low values, the effect of heterosis when crossbreeding was introduced was hardly visible. Swedish law requires sick animals to be treated, regardless of production system. However, registration of disease treatments in the cattle database is voluntary, and not all veterinarians report treatments very carefully. Consequently, some registrations of treatments may be missing, resulting in assumptions about the level of diseases in the present simulations that are too low. This issue may have caused an underestimation of the effects of crossbreeding in relation to health traits.

The prevalence of mastitis, reproduction diseases, and metabolic diseases simulated in the purebred scenarios are in accordance with Jönsson (2015), who estimated frequencies of diseases in SR and SH. However, frequencies in that study were lower for feet and leg diseases (2.1%) than those in our simulations of hoof and leg diseases. A possible reason for the considerable difference is that Jönsson (2015) only included information from veterinarians, whereas we also included information from hoof trimmers.

Disease risks in dairy cows tend to rise over lactations (Fleischer et al., 2001), which may counteract the benefits of heterosis in health at the herd level when the average age of the cows increases. In the present study, the presence of more older cows when crossbreeding was introduced in a purebred herd may explain why the number of mastitis treatments increased in the organic production system. The favorable breed effect of SR on mastitis risk was stronger in the conventional production system (Table 1), and the number of mastitis treatments therefore decreased in that system. The larger proportion of older cows in the crossbreeding scenarios did not increase the number of other disease treatments, although it may still have counteracted the effect of heterosis.

The age distribution among cows in the scenarios suggests that the cows stayed longer in the crossbreeding herds, which is in accordance with findings from other studies. Heins et al. (2012) estimated +20.1% and 21.4% higher survival rates for third- and fourth-parity Scandinavian Red × Holstein crossbred cows compared with Holstein in 6 Californian commercial herds. Across Danish herds grouped in 3 different production levels, Clasen et al. (2019) found between 7.5% and 15% higher survival rates from first to third calving in F_1 crossbreds between Nordic Red and Holstein compared with Holstein.

Economic Output

Two-breed terminal crossbreeding and rotational crossbreeding, under Swedish conditions and within the selected input parameters, proved to increase annual CM relative to that observed in pure-breeding regardless of production system. Rotational crossbreeding was most beneficial because all animals in the herds were crossbreds, which ensured that a greater benefit of heterosis was achieved at the herd level. Nevertheless, the terminal crossbreeding scenarios showed that, despite only 31% of the production cows in the herd being crossbreds, CM could still be raised by 1 to 2%. The monetary gains were lowest for the terminal crossbreeding scenario in the conventional production system, which was €20 per cow-year. That sums up to €2,000 per year in a 100-cow herd, which essentially only covers small investments. However, none of the scenarios were optimized from an economic point of view. For example, optimized use of SS and BS in both crossbreeding strategies may have led to greater profitability, especially from a genetic perspective. On top of that, with the advantage of having breeding values in purebred animals, the terminal crossbreeding strategy could possibly catch up and cancel the difference in CM between it and rotational crossbreeding.

Changing from pure-breeding to any of the crossbreeding strategies decreased the number of young stock and thus the total number of animals in the herd. This situation permits a saving on resources (e.g., labor, buildings, and farmland), but that was not factored into the economic calculations of this study. Thus, the benefit of crossbreeding may be larger than estimated in the present study. In Sweden, dairy heifers are often used for nature preservation, which is highly subsidized by the European Union and the Swedish government. This practice also means that during the 4- to 6-mo grazing period heifers are relative low or no cost or maybe even profitable. However, that is not the case for all dairy farmers throughout the world, meaning a reduction of young stock may be even more beneficial for herds without this privilege.

Possible heterosis effects on feed efficiency were not considered in this study because heterosis estimates for feed efficiency in dairy cattle are still relatively understudied. However, Shonka-Martin et al. (2019) made comparisons of purebred Holstein with rotational 3-breed crossbred cows (Viking Red, Montbéliarde, and Holstein) and found significantly ($P < 0.05$) higher feed conversion ratios in the crossbred cows during the first, second, and third lactations. Furthermore, the crossbreds produced the same levels of fat and protein on lower feed intake as the purebreds. This outcome suggests that crossbreds may be more profitable because they can generate lower feed costs without a loss in production income. Furthermore, improved feed efficiency potentially reduces the environmental impact from dairy production (Bell et al., 2011).

Studies of the economic outputs of dairy herds differ in various respects, for example, in what they include in income and costs, prices, country studied, management conditions, breeds, and type of study (simulation, commercial or experimental herds). Furthermore, few studies have estimated the economic benefits of crossbreeding between Holstein and breeds similar to SR. In New Zealand, Lopez-Villalobos et al. (2000) simulated a 3.6% increase in net income per cow in a comparison of a 2-breed rotational crossbreeding herd (Ayrshire × Holstein) with a pure Holstein herd. This study was based on somewhat different production from the Swedish system, including lower milk yields, all-year grazing, and seasonal calving. In the study by Heins et al. (2012), the projected daily profit per cow was 4% higher in F_1 crossbreds of Scandinavian Red × US Holstein, than it was in purebred US Holstein. The result in this study was estimated from 6 commercial Californian dairy herds. However, health costs were not included in the economic calculations. In addition, the studies by Lopez-Villalobos et al. (2000) and Heins et al. (2012) did not include beef × dairy crossing. In the first published demonstration of SimHerd Crossbred, rotational crossbreeding between Holstein and Danish Red increased yearly net return per cow by 9.8% compared with pure-breeding with Holstein (Østergaard et al., 2018). This study was based on Danish conditions, which are somewhat similar to those in Sweden. However, the input parameters and breeds differed from the present study. For example, Østergaard et al. (2018) simulated slightly higher milk yield in crossbreeding compared with pure-breeding, and the frequency of disease treatments and replacement rate were somewhat higher.

Sensitivity Analyses

The sensitivity of CM to the difference in production performance between 2 breeds in Figure 2 shows the importance of using economically similar breeds in a crossbreeding system if the goal is to achieve higher profits than pure-breeding. This result can be translated to any breed comparison in any country or region. It is an incentive for breeders of the lowest-producing breed to continue the genetic progress in the breed to keep it attractive for crossbreeding. The change of the relative breed performance had a lower effect on CM for terminal crossbreeding than rotational crossbreeding because the latter included more genes of the inferior breed (i.e., SR). Estimation of proper breed differences is therefore crucial for having the most reliable estimates for simulating the effects of crossbreeding.

Reducing the milk price by 20% had a higher positive effect on the relative CM between the pure-breeding scenario and the crossbreeding scenarios than increasing the milk price by 20% (Figure 3), while changing the feed price had almost the opposite effect (Figure 4). The purebred scenario had the highest income from milk production but also the highest total costs (Table 5). Reducing the milk price while keeping the costs constant led to the CM changing at a relatively faster rate in the purebred scenario compared with the crossbreeding scenarios, making the difference between the scenarios larger. On the other hand, when the feed price, which caused about 85% of the total costs, was reduced without changing the milk price, the relatively higher milk income in the purebred scenario caused a relatively faster increase in CM, making the difference from the crossbreeding scenarios smaller.

The patterns of the sensitivity analyses are in accordance with similar analyses made by Heins et al. (2012). The study compared Holstein with F_1 crossbreds of Normande × Holstein, Montbéliarde × Holstein, and Scandinavian Red × Holstein in 6 commercial herds in California. When the feed costs increased by 37.5%, the difference in projected profit per cow-day increased in favor of crossbreds, showing same tendency as in the present study. Similar to present study's finding, the effect of increasing milk price by 32% was in favor of the purebreds, while the advantage of decreasing milk price by 32% was in the crossbreds. Unlike the present study, feed costs and other costs associated with replacement heifers remained fixed when feed costs (for cows) and milk price changed in the study by Heins et al. (2012). However, they also investigated the effect of increasing costs of replacement heifers by 35%, and the effect was similar to the effect of increasing feed costs for the cows.

The ratio between milk and feed prices has historically switched between favorable and unfavorable within short periods of time (IFCN, 2019). However, within the last decade, feed prices have been rapidly increasing due to higher competition over arable land. This situation provides an incentive for farmers, in Sweden and other countries, to introduce crossbreeding in their herds for reduced feed costs (for both cows and young stock) and potentially improved feed efficiency (Shonka-Martin et al., 2019).

Breeding

The impact of crossbreeding on genetic progress was not simulated in this study. However, breeding decisions concerning the purebred animals in a terminal crossbreeding system should be investigated as a selection strategy. In particular, the use of SS in combination with BS may potentially improve economic benefits (Ettema et al., 2017). Improved genetic levels will benefit the crossbred animals as well. However, breeding values are currently not estimated for crossbred dairy cattle in Sweden. Consequently, selection of the genetically best production cows is easier in a terminal crossbreeding strategy, in which all breeding candidates are purebred animals, than in a rotational system. Estimated breeding values in crossbred animals, or for crossbred performance in purebred animals, would be a valuable tool, enabling farmers to select among females in a rotational crossbreeding system and to select sires for use in a terminal crossbreeding system. As genotyping technologies and genomic selection are currently developing rapidly (VanRaden and Cooper, 2015), breeding values for crossbreeding may be a reality in the near future.

Implementation of Crossbreeding in a Dairy Herd

The implementation of crossbreeding in a herd is a long-term investment. Assuming an optimal breeding and culling strategy, the transition period from having only purebreds in a herd to a 2-breed rotational crossbreeding system may be lengthy: it may be 15 to 20 yr before breed proportions have stabilized. A 2-breed terminal crossbreeding system may have a shorter transition period depending on the desired nucleus size. Effective transition to crossbreeding may require additional use of SS and a strict voluntary culling strategy during the early period. The most effective transition strategy, both economically and in terms of time needed, needs to be investigated.

Most herds in Sweden are mixed herds with SR and SH rather than entirely one breed or the other. With the average herd size currently being around 90 cows (Växa Sverige, 2018), logistical problems with terminal crossbreeding could arise in which 2 (small) nuclei would be present in addition to the crossbred part. The risk of having a shortage of purebred heifers for replacement might lead to maintenance of the status quo or to the use of a rotational system or a suboptimal terminal crossbreeding system with only a small proportion of crossbreds.

In herds with low fertility, poor health, or both, crossbreeding may be a beneficial tool because heterosis is usually largest in functional traits with low heritability (Sørensen et al., 2008). However, studies show that it is not only herds with a low level of management, expressed as level of production, that benefit from crossbreeding (Bryant et al., 2007; Lembeye et al., 2015; Clasen et al., 2019). The economic benefits of crossbreeding at different herd management levels, including herd dynamics, need to be investigated further.

The 2 crossbreeding systems simulated in this study showed strengths and weaknesses in comparison with each other, and the choice between them depends on the farmer's preferences and the current herd situation. Obviously, raised profitability from crossbreeding will be a high priority, but improvements in health, fertility, and production may be highly prioritized as well. Potentially, an improvement in health and fertility resulting in "problem-free" production could be more valuable than is indicated by the individual cost items used here. Farmers empathize with their animals (e.g., Bock et al., 2007) and would rather have healthy animals for ethical reasons. Additionally, sick and subfertile cows create more work and sometimes necessitate special procedures (e.g., milking mastitic cows last). These extra labor costs were not accounted for in our calculations.

CONCLUSIONS

This simulation study showed that terminal and rotational crossbreeding strategies using SR and SH can improve profitability in average Swedish organic and conventional dairy herds with purebred SH only. The main benefits of heterosis were expressed in fertility traits and survival, which ensured that fewer replacement heifers could be kept and that a lower replacement rate was present. The improved fertility in the herds permitted additional use of BS, producing slaughter calves with a higher value. In addition, heterosis on milk yield was favorably expressed in only minor decreases in 305-d production as compared with purebreeding. The largest economic benefits were shown for rotational crossbreeding, in which all animals in the herd were crossbreds and expressed 67% of the full heterosis. In the terminal crossbreeding system, 31% of the animals were crossbreds expressing full heterosis. The 2 crossbreeding strategies were not economically optimized; potentially, they could generate even larger economic benefits. Some aspects of the implementation of crossbreeding in a herd remain to be investigated, such as the economically optimal breeding strategy, genetic improvement, and transition strategies.

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