Economic opportunities of using crossbreeding and sexing in Holstein dairy herds

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ABSTRACT

With the increasing availability of sexed semen, farms have the opportunity to select genetically superior dams to produce their replacement animals and to produce crossbred calves for beef production of higher economic value than the remainder of the herd. However, higher costs and reduced fertility of sexed semen complicate the decision of when and to what extent sexed semen should be applied in a herd. The objective of this study was to explore the economically optimal utilization of sexed semen and crossbreeding among North Rhine-Westphalian dairy farms in a holistic single-farm model. For the analysis, we derived a representative sample of farms from Latin Hypercube sampling based on the observed distribution of farm characteristics from official North Rhine-Westphalian Farm Structure Survey data. Market- and technology-related input parameters such as output prices and sexed semen accuracy and fertility were included in the sampling procedure. Modeling results of the systematic sensitivity analysis were evaluated in a statistical meta-model. We found that the profit-maximizing utilization of sexed semen and crossbreeding was highly heterogeneous among the farms. Farms with lower stocking densities, <2 livestock units (LU)/ha, were generally found to produce excess heifers for sale, whereas farms with stocking densities >2 LU/ha were producing crossbred calves and using sexed semen only to produce replacement animals. On average, female-sexed dairy semen was used on 25.3% of all inseminations. Beef semen (both sexed and conventional) for producing crossbred calves was used in an average of 21.5% of the inseminations. The combination of sexed semen and crossbreeding increased profits from €0 to €568 per cow per year, with an average of €79.42 per cow per year. Farms characterized by low stocking densities (<2 LU/ha) and above-average replacement rates (>40%) were found to have higher profit increases as a

result of selling more heifers from the use of sexed semen. Overall, sexed semen and crossbreeding adoption were most sensitive to stocking density and average cow longevity, as well as to additional costs for sexed semen and sexed semen accuracy. Our results show the potential of modern breeding technologies to improve dairy farm profits and the need to judge their profitability in the light of farm-specific production settings.

Key words: sexed semen, crossbreeding, farm model, economics

INTRODUCTION

The average lifespan of cows has slightly increased over the past decades. However, cow vitality and fertility remain important issues in German high-input/high-output dairy herds (Martens, 2016; Römer et al., 2018). On average, Holstein cows are culled after only 2.7 lactations in Germany, with almost 30% leaving during the first lactation (Römer et al., 2009; Arbeitsgemeinschaft Deutscher Rinderzüchter, 2018). As a consequence, herd replacement rates remain high and, without the use of sexed semen, almost all female offspring are required for replacements in the milking herd (De Vries et al., 2008).

The potential for economic issues in such a limited lifespan of dairy cows is high. A high replacement rate causes considerable rearing and replacement costs per cow. As a by-product of the necessary purebred female offspring, a high share of purebred male calves per average cow is produced with low weight gains and reduced meat quality compared with their beef breed counterparts. The male calves are subsequently of relatively low economic value and contribute little to overall farm profits (Wolfová et al., 2007). A high number of rearing heifers relative to the productive herd also implies higher nutrient excretion per productive cow with related costs required to comply with environmental legislation, such as the recently revised Fertilization Ordinance (FO) in Germany. There is also higher feed consumption per productive cow, again with detrimental impacts on environmental performance (Weiske et al., 2006).

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The application of sexed semen has been growing rapidly in the dairy industry in recent years (Holden and Butler, 2018). Sexed semen allows the sex of a calf to be predetermined with an accuracy around 90% (Seidel, 2014), which opens new possibilities to address the aforementioned issues. However, compared with conventional semen, prices for sexed semen remain higher (Schneichel, 2017), and the lower conception rates from 70 to 90% (DeJarnette et al., 2011; Healy et al., 2013; Maicas et al., 2020) increase the number of required inseminations (Seidel, 2014).

In addition to using sexed semen, farmers may use beef semen to produce dairy-beef crossbred calves. The resulting crossbred calves perform better in fattening systems, yielding higher sales value (Wolfová et al., 2007) and improving the overall efficiency of the dairy-beef chain. Combining the use of sexed semen and crossbreeding constitutes a promising alternative to conventional breeding methods. It may improve economic results, deliver a higher proportion of female calves, and allow for selecting only cows with the highest genetic ranking for replacements. Crossbred calves that perform better in fattening may be produced from the remaining dams of the herd.

Different aspects of sexed semen with and without crossbreeding have been addressed in the literature. McCulloch et al. (2013) studied the influence of key variables such as market, management, and technology on the profitability of using sexed semen in a high-yielding Holstein herd in Colorado. Their results suggested that management variables (e.g., conception rates) and the price of dairy heifer calves had a significant effect on the net present value gain per cow, whereas the cost of sexed semen and milk price had relatively little effect on profitability. Potential effects on the rate of expansion for heifers and lactating cows in a pasture-based system using sexed semen were modeled by Murphy et al. (2016). Five different breeding strategies were analyzed and showed that the scenario where sexed semen was used on heifers and a targeted group of cows facilitated the fastest possible expansion. A stochastic, bioeconomic spreadsheet model was employed by Cottle et al. (2018) to analyze the profitability of using sexed semen in a high-input/high-output dairy herd. Their findings suggested that inseminating both heifers and cows with sexed semen was the most profitable in the simulation. The study emphasizes the relatively elevated effect of pregnancy rate and the genetic value of dairy bulls for determining the financial advantages of sexed semen usage. Ettema et al. (2017) combined the simulation models SimHerd (Østergaard et al., 2005) and ADAM (Pedersen et al., 2009) to study the hypothesis that sexed semen increased genetic gain and

overall net return depending on herd management. The hypothesis that the potential for beef semen to increase genetic level would be herd-specific was supported by their findings. However, they concluded that none of the scenarios modeled were profitable under Danish circumstances when the value of the increased genetic level was not included.

Given that the existing literature found large differences in the driving factors for the profitability of sexed semen and beef semen use for different types of dairy farms, a proper assessment should incorporate a population of farms and their characteristics for the evaluation of profitability. However, a detailed whole-farm analysis studying the profit maximizing shares of sexed dairy semen, sexed beef semen, and conventional beef semen (crossbreeding) depending on farm characteristics is still missing. The objectives of this paper were therefore 3-fold. First, we determined the extent to which dairy farms in our study region would use sexed dairy semen, sexed beef semen, conventional beef semen, or a combination of these under profit-maximizing behavior. Second, we explored factors explaining differences in the adoption rates of sexed dairy semen and beef semen (both sexed and conventional beef semen) between different farms or market conditions or both. Third, we studied the potential economic benefits for different types of dairy farms and the extent to which they rely on market conditions.

MATERIALS AND METHODS

A 3-step modeling framework was used to assess the profit-maximizing shares of sexed semen and beef semen use (Figure 1). The method was largely based on a meta-modeling approach proposed by Lengers et al. (2014) and Kuhn et al. (2019).

At first, a representative sample for the farm population including draws for input and output prices and sexed semen characteristics was generated by Latin Hypercube sampling (**LHS**). The sampling was based on data from official agricultural statistics. In a second step, each of the sample farms was simulated in the single farm optimization model FarmDyn (Lengers et al., 2013, 2014; Kuhn et al., 2019). To depict the economic effects of using sexed dairy semen and (sexed) beef semen, the model was solved 2 times for each farm. First, the model was solved without the possibility of using sexed dairy semen and beef semen for crossbreeding (baseline). In a second run, both sexed semen and beef semen (both conventional and sexed beef semen) were made available. Note that the share of sexed dairy, sexed beef, and conventional beef semen was an endogenous variable in our optimization model such

that the model would simulate optimal usage intensity (which may be zero) to address the research questions. In a third step, a statistical meta-model was derived to explain overall sexed semen/beef semen share and profit deltas resulting from sexed semen and beef semen usage.

Sampling Procedure

Our analysis examined specialized dairy farms in the German federal state of North Rhine-Westphalia. Roughly 10% of the German dairy population is based in North Rhine-Westphalia, with more than 4,300 farms specializing in dairy production (Statistisches Bundesamt, 2018). Selling their male calves 2 wk after birth, these farms generally produce their own replacement heifers. Additional heifers might be sold for replacements or slaughter. Distributions reflecting single farm data for the study region were used from the German Farm Structure Survey (FSS) 2016, as reported by Kuhn et al. (2019). The data covered factors regarding farm endowments, such as farm sizes, grassland shares, stocking densities, and manure storage capacities as explanatory factors. Regional data regarding crop

production, such as maize silage and grassland yields, were taken from KTBL (2019). Ranges of input coefficients for animal prices, milk yields, lactation lengths, and first calving ages were derived from KTBL (2018). Data on sexed semen accuracy, and additional insemination efforts (**IE**) when using sexed semen (sexed semen conception rate) were drawn from Seidel (2014) and Butler et al. (2014). The explanatory factors and their ranges are depicted in Table 1. Because empirical distributions for input parameters not covered in the Farm Structure Survey were not available, uniform distributions for these parameters were assumed. The correlation between these parameters was assumed to be zero, reducing the risk of multi-collinearity in the statistical meta-model. To depict the whole value range of the model input parameters, a sample of the farm population of ~1,700 farms was generated using LHS (McKay et al., 1979).

Farm Modeling

For the farms derived from the sampling procedure, the adoption and economic gain of sexed semen and crossbreeding were estimated. For the analysis, we

Figure 1. Overview of modeling framework, adapted with permission from Kuhn et al. (2019) and Lengers et al. (2014).

enhanced the dynamic, mixed-integer linear programming model FarmDyn (Lengers et al., 2013, 2014; Kuhn et al., 2019) to incorporate adequate representations of herd dynamics and breeding techniques. FarmDyn is an open-source and open-access bioeconomic single farm model written in the General Algebraic Modeling Language (GAMS Development Corporation, 2019). For further technical information regarding the model FarmDyn, see the technical documentation (Britz et al., 2016). Its modular structure (illustrated in Figure 2) allows simulation of different farming types, including dairy, suckler, beef, and arable farms. Indivisibilities in investments and labor use, such as buildings and machinery, are captured by the use of integer variables (mixed-integer linear programming; MILP). Farm management decisions; for example, feeding, use of sexed semen or crossbreeding, manure management, and labor distribution, are modeled with a monthly resolution (partially every 2 wk). The model is parameterized for German conditions with the use of detailed farm planning data provided by KTBL (2018) and LfL Bayern (2018). Model results were validated with individual project case study data.

For the current study, we used the deterministic comparative static version of the model, which maximizes the net present value over a predefined planning horizon of farms using farm-household resources (labor, land, financial assets). A rational, fully informed, and risk-neutral decision maker was assumed. We refrained from modeling risk and risk behavior because we lacked any defensible source to parameterize risk behavior in the required detail. Moreover, as no closed-form determination of variance-covariance matrices for the decision variables was possible, the application of a mean-

variance analysis (Markowitz, 1952) was not feasible. The influence of variability in input coefficients across farms on the overall net present value and other factors was analyzed by a structured sensitivity analysis.

As investment decisions were not at the core of our analysis, we performed a comparative static analysis where continuous reinvestments for machinery and sunk costs for housing were assumed and related costs annualized. Investments in new housing were disabled to capture the short-term effects of sexed semen and crossbreeding usage. Consequently, herd dynamics were depicted in a steady-state model as described in the following section such that effects of the advanced breeding methods on an average production year were depicted. The model was constrained by available resources, possible production processes, allowed crop rotations, off-farm working opportunities, and 2 restrictions relating to agri-environmental legislation. These were the German Fertilization Order, as the implementation of the European Nitrates and Water Framework Directives, and the greening obligations under the First Pillar of the Common Agricultural Policy.

The dairy module characterized one of the possible farm branches in the model. Here, mass flows as feeds, manure, and animals were described, and linked to the economic optimization part of the model. Feed rations were optimized endogenously according to the nutrient and DM constraints defined by the Zifo2 feed optimization application (LfL Bayern, 2016). Also, different feeding regimens such as grazing, partial grazing, or nongrazing were accounted for, depending on the endowments present on the farm. Manure handling was assumed to be outsourced to a contractor, and manure have been spread on own fields or, with additional

Table 1. Characterization and sources of explanatory factors

Explanatory factor	Minimum	Median	Maximum	Data source
Farm size (ha)	8.14	61.24	221.35	FSS 2016 in Kuhn et al. (2019)
Grassland share (%)	6	51	100	FSS 2016 in Kuhn et al. (2019)
Grassland yield (t of DM/ha)	6.19	6.94	7.69	KTBL (2019)
Maize silage yield (t of fresh matter/ha)	42.9	46.55	50.2	KTBL (2019)
Stocking density (livestock units/ha)	0.63	1.75	5.94	FSS 2016 in Kuhn et al. (2019)
Milk yield (kg of ECM/ha)	6,800	9,400	12,000	KTBL (2018)
Average cow longevity (lactations/cow)	1.7	4.15	6.6	KTBL (2018)
Calving interval ¹ (d)	365	408.5	452	KTBL (2018)
Additional costs female-sexed semen doses (€/n)	13	24.5	36	Besamungsverein Neustadt (2019)
Additional insemination effort sexed semen (n)	0	0.575	1.15	Own calculation based on Butler et al. (2014)
Sexed semen accuracy (%)	75	87.5	100	Seidel (2014)
Price (€/head)				
Heifer	1,040	1,490	1,940	KTBL (2018)
Beef bull calf	70	195	320	KTBL (2018)
Beef heifer calf	40	145	250	KTBL (2018)
Dairy heifer calf	10	50	90	KTBL (2018)
Dairy bull calf	10	80	150	KTBL (2018)

¹The minimum calving interval was set to 365 d to fit the assumptions made in the Materials and Methods section.

Figure 2. Simplified flowchart illustrating the main modules of the model FarmDyn. Source: Britz et al. (2016).

costs, exported to other farms. Land leasing and buying of forages were disallowed to depict the short-term effects of sexed semen and crossbreeding usage only.

The model differentiated between calf-, heifer-, and cowherds of different sex and ages. Each animal of a herd represented an average animal of the herd in the model. Therefore, production parameters such as milk yield, lactation profile, breeding value, number of services, and pregnancy rate were equal among animals within each herd group.

Default modeling parameters were specified to reflect the range of dairy farms in the study area. Milk yields between 6,800 and 12,000 kg of ECM were realized (KTBL, 2018). The roughage intake was assumed to be at least 60% of the total DMI of the cows. Cows were not given access to pastures, and year-round calving was assumed. The availability of grass and maize silage per cow as an endogenous variable reflected the individual farms' endowments (as mentioned above).

For heifers, an average of 1.6 services, and for cows 2.3 services per pregnancy were assumed when conventional semen was used, implying a fixed heat detection rate of 70% (Römer et al., 2013). Cows and heifers being culled due to reproductive (exceeded maximum number of services) or nonreproductive (e.g., lameness, mastitis) reasons were implicitly captured by an exogenously assumed average cow longevity in the herd. In

addition, an annual mortality rate of 5% was applied to the model (KTBL, 2018).

Depending on the specific farm characteristics, sufficient replacement heifers were reared, targeting 23 to 25 mo as age of first calving. Depending on the age of first calving, feed composition, labor requirements, and final weight were adapted accordingly. Surplus calves were assumed sold to the market at <1 mo of age.

Implementation of Sexed Semen and Crossbreeding

In addition to conventional dairy semen, the opportunity to use sexed dairy, sexed beef, or conventional beef semen was introduced into the above-described farm model as an endogenous decision.

For the conventional and sexed beef semen, it was assumed that Belgian Blue sires were used for crossbreeding. Costs for conventional beef semen were assumed to be equal to those for conventional dairy semen in the model. Similarly, sexed beef semen was assumed to be equal in costs and fertility as sexed semen of a Holstein sire. Crossbred calves were assumed to be sold right after birth; additional on-farm fattening was not considered.

Regarding sexed semen (both dairy and beef sexed semen), it was assumed that when sexed semen was used on the first service, it was used throughout the

remaining services until a pregnancy was achieved. The conception rate of sexed semen for both heifers and cows varies in the analysis (as mentioned above) and was assumed to be 75 to 100% of the conception rate of unsorted conventional semen (Butler et al., 2014). To determine the effect of the reduced conception rate of sexed semen on the average number of services required for a pregnancy (IE), conception rates depending on the service number by Kuhn et al. (2006) were evaluated for heifers, while a fixed conception rate of 35% was assumed for conventional unsorted semen for cows. We assumed that for a successful insemination using sexed semen, the same cumulative probability that any of the inseminations have been successful as with conventional unsorted semen would be required. Given the average of 1.6 services for heifers and 2.3 services for cows, an additional average increase of 0 to 1.15 services (again varied in the analysis) was derived when sexed semen was used. This way, the higher conception rates of using sexed semen on heifers compared with multiparous cows were reflected in the model. Herd-specific parameters that vary in the analysis are displayed in Table 1, whereas default static input values are presented in a supplemental material (Supplemental Table S1; <https://doi.org/10.3168/jds.2019-17354>).

The additional number of services when using sexed semen had several implications on the model. In heifers, the average age of first calving was (involuntarily) shifted upward when sexed semen was used. Consequently, additional feed and labor were required, leading to an increase in rearing costs. In multiparous cows, the involuntarily extended lactation length led to a change in the lactation profile and fewer calvings per year. For both heifers and cows, the additional input costs per successful sexed semen insemination were assumed to be the total IE multiplied by the price premium of sexed semen. Further technical aspects of the specific calculation of herd sizes and calving distributions within the modeling framework are presented in the supplemental material (<https://doi.org/10.3168/jds.2019-17354>).

Among other impacts, the use of sexed semen and beef semen has an effect on dystocia (Norman et al., 2010). To depict the effect of differing dystocia risk among heifers and cows regarding bull calves, heifer calves, and beef calves, we used dystocia risk scores and related costs as described by McCulloch et al. (2013) (Supplemental Table S1; <https://doi.org/10.3168/jds.2019-17354>).

Literature has shown the importance of genetic improvement as an economic factor for the use of sexed semen or beef semen or both (McCulloch et al., 2013; Ettema et al., 2017; Cottle et al., 2018). In general, genetic improvement is obtained by mating animals so

that their offspring are genetically superior compared with the population in terms of the breeding goal (De Vries, 2017). Through the use of sexed semen, genetically superior animals can be selected to produce the next generation of replacement heifers, thus improving the genetic level of the herd. To increase the genetic level even further, beef semen can be used on genetically inferior multiparous cows, so that their offspring do not enter the milking herd. We based the calculation of genetic merit on the results outlined by Ettema et al. (2017). Similar to their approach, we valued 1 genetic standard deviation (SD) of the Nordic Holstein breeding goal at €89 per cow-year. Improvements in genetic level for using sexed dairy semen on heifers and beef semen (sex sorted and unsorted) cows were derived from their results by linear regression. Breeding 1% of all heifers with sexed semen resulted in an estimated genetic increase of ~0.001 SD units of the breeding goal while breeding 1% of all multiparous cows with beef semen resulted in a genetic increase of ~0.0017 SD units of the breeding goal. The resulting economic value of differences in the genetic level induced by sexed semen and beef semen use (genetic return) was then calculated by multiplying the difference in genetic SD units by €89.

Statistical Meta-Modeling

To quantify which factors significantly affected the adoption of sexed semen and beef semen, as well as the profit gain resulting from sexed semen and beef semen use, we constructed a statistical meta-model for each of the 3 cases. The meta-models approximated the input and output transformations of the FarmDyn model, resulting in a simplified statistical model summarizing all simulations runs of the sample population. The meta-models were specified as multiple linear regression models, where the explanatory factors displayed in Table 1 were defined as the independent variables and the share of sexed semen, beef semen, and profit gain from sexed semen and beef semen use as the dependent variables respectively. The statistical analysis was conducted using the software R (R Core Team, 2017).

RESULTS

We found the profit-maximal sexed semen and crossbreeding utilization among the studied farm population to be highly heterogeneous, reflecting the distribution of farm characteristics and input coefficients described in Table 1. Under these assumptions, 93.3% of the farms were simulated to use female-sexed dairy semen (X-chromosome enriched) on heifers at least once.

Table 2. Multiple linear regression model output (meta-model of the single farm model FarmDyn) on overall sexed semen share, beef semen share, and profit deltas resulting from sexed semen and crossbreeding usage (dependent variables) for North Rhine-Westphalian dairy farms¹

Variable	Dependent variable (β -coefficient)		
	Share sexed dairy semen (all inseminations)	Share beef semen (all inseminations)	Profit delta sexed semen and crossbreeding
Cow longevity (no. of lactations/cow)	−0.471***	0.091***	−0.307***
Additional insemination effort sexed semen (n)	−0.418***	−0.070***	−0.287***
Stocking density (livestock units/ha)	−0.307***	0.689***	−0.455***
Calving interval (d)	−0.279***	−0.047***	−0.188***
Dairy bull calf (€/head)	−0.073***	−0.079***	−0.070***
Beef bull calf (€/head)	0.062***	0.124***	0.106***
Additional costs: female-sexed semen doses (€/n)	−0.047***	−0.010	−0.037**
Milk yield (kg of ECM/ha)	−0.046***	0.093***	−0.032*
Price heifer (€/head)	0.032**	−0.048***	0.220***
Grassland share (%)	0.025*	−0.066***	0.081***
Sexed semen accuracy (%)	0.022	0.027*	0.076***
Farm size (ha)	0.014	−0.079***	−0.133***
Beef heifer calf (€/head)	0.013	0.167***	0.080***
Maize silage yield (t of fresh matter/ha)	0.012	0.002	0.026
Manure storage capacity (m)	−0.010	−0.013	−0.010
Dairy heifer calf (€/head)	−0.005	−0.001	−0.001
Grassland yield (t of DM/ha)	−0.003	−0.014	0.019
Constant	−0.000	−0.000	−0.000
Observations	1,736	1,736	1,736
R ²	0.616	0.621	0.505
Adjusted R ²	0.613	0.617	0.500
Residual SE (df = 1,718)	0.622	0.619	0.707
F-statistic (df = 17; 1,718)	162.442***	165.411***	103.150***

¹Reported coefficients are standardized (β -coefficients). The table was generated using the R package “stargazer” (Hlavac, 2018).

* $P < 0.1$, ** $P < 0.05$, *** $P < 0.01$.

Furthermore, 6.4% of the farms were simulated to use male-sexed beef semen (Y-chromosome enriched) on heifers at least one time. Female-sexed dairy semen used on cows was found to be profit maximal in 6.9% of the farms to some extent. Male-sexed beef semen on cows was found to be utilized in 0.1% of all farms. Beef semen use, both sexed and conventional, was found to be used in 49% of the farms for at least one insemination. On the farms that used beef semen, an average of 76.2% of the cows and 13.3% of the heifers were bred with beef semen.

Female-sexed dairy semen was used on an average of 25% of all inseminations in the optimum. An average of 66% of all heifers, and 5% of all cows, were bred with female-sexed dairy semen. The average herd replacement rate was 22%, with an average cow longevity of 4.46 lactations per cow among the sample population.

Using beef semen for crossbreeding (both conventional and sexed semen) was found to be profit maximal for an average of 21% of all inseminations. Conventional beef semen was used on an average of 37% of all cow inseminations and 6.5% of all heifer inseminations.

On average, 2% of all heifers and less than 1% of all cows were bred with sexed beef semen in the simulation results.

Drivers of Overall Sexed Semen and Crossbreeding Usage

To identify the main drivers of these profit-maximal shares of sexed semen and crossbreeding usage, the statistical meta-model described in the previous section was analyzed. The standardized regression coefficients for the explanatory variables are displayed in Table 2. Although many of the explanatory variables were found to have a significant effect on the dependent variables, a few explained a greater part of the variance. This was expected given the high number of observations and the absence of measurement and reporting errors. In the case of the relative share of female-sexed dairy semen used on all inseminations on a farm, the β -coefficients of management factors such as cow longevity, as well as technology factors such as conception rates (expressed through additional required IE), and general farm endowment factors as the overall stocking density were found to have the largest absolute effect on the overall profit maximal adaptation.

The top half of Figure 3 shows the simulated relative share of female-sexed dairy semen used on the farms, depending on the farms' individual stocking density and average cow longevity. Supplemental Figure S1

Figure 3. Profit maximizing share of female sexed dairy semen used on all inseminations (top), compared with the share of beef semen (sum of sexed beef semen and conventional semen) used on all inseminations (bottom) in the North Rhine-Westphalian study population. Each dot represents a farm in the sample population. LU = livestock units.

(<https://doi.org/10.3168/jds.2019-17354>) displays the same graph but with the sexed semen conception rates (expressed as additional IE) on the color axis. From the 2 graphs, it can be seen that very high sexed semen utilization shares up to 100% of all insemination were found to be profit-maximizing for farms with stocking densities <1.5 LU/ha, combined with below average cow longevity (<3 lactations per cow), and high sexed semen conception rates (>90% of conventional semen conception rate, requiring fewer additional inseminations when sexed semen was used). As indicated by the β -coefficient displayed in Table 2, herds with high average cow longevity (>3 lactations per cow) were, in general, found to be utilizing sexed semen significantly less than farms with below-average cow longevity. Farms using sexed semen on few inseminations were mostly characterized by higher stocking densities (>2 LU/ha), combined with above-average cow longevity (>4 lactations per cow), and low sexed semen conception rates (<80% of conventional semen conception rate).

The bottom half of Figure 3 displays the simulated relative share of beef semen (sexed and conventional beef semen jointly considered) used on the farms for producing crossbred calves, again depending on the farms' individual stocking density and average cow longevity.

Farms with stocking densities >2 LU/ha and average cow longevity >5 lactations per cow were simulated to have high uptakes of beef semen, mostly ranging from 70 to 80% of all inseminations in the optimum. Farms with lower stocking densities <2 LU/ha or lower than average cow longevity (<3 lactations per cow) or both, in contrast, were simulated to have a wider range of beef semen uptake between 0 and 60%. As displayed by the β -coefficients in the “Share beef semen” column of Table 2, aside from stocking density, a multitude of market factors such as beef heifer calf and beef bull calf prices had a positive impact on overall beef semen uptake, whereas overall farm size (ha), dairy bull and heifer prices, as well as sexed semen conception rates, had a negative impact on overall uptake. When beef semen was used in a farm, the share of sexed beef semen on all beef semen used was ranging from 0 to 100% among the simulated population. On average, 2.7% of the beef semen used was sexed beef semen.

Effects on Farm Profitability

The potential economic benefits of using sexed semen and crossbreeding were again found to be highly heterogeneous within the North Rhine-Westphalian dairy

farm population, ranging from €0 to €568/cow and year. On average, farms in the population sample could increase their profits by €79.42/cow and year (median €59.52 per cow and year) by applying sexed semen, crossbreeding, or both. Multiplied by a simulated average herd size of 91 cows, the mean sexed semen and crossbreeding induced profit increase would add up to approximately €7,225 per farm per year. When only sexed and conventional dairy semen (no crossbreeding) was made available to the farms, the average profit increase was €65.35 per cow (median €40.44 per cow) compared with the baseline. In the run where only conventional beef semen and conventional dairy semen (no sexed semen) was made available to the farms, the average profit increase was €10.06 per cow (median €8.33 per cow), with a range of €0 to €227 per cow among the sample population, reflecting the possibility to use crossbreeding.

Table 2 reports on a meta-model that analyzed these profit differences. The variable coefficients in the third column indicate that the economic benefits of utilizing sexed semen and crossbreeding were driven by market factors such as heifer, beef bull calf, and beef heifer calf prices. On the other hand, increasing stocking densities, cow longevity, and lower sexed semen conception rates were found to diminish additional profit gains compared with the baseline, where neither sexed semen nor crossbreeding was used on the farms.

Figure 4 shows additional profits per cow when sexed semen and sexed/conventional beef semen were made available to the farm population compared with the baseline. The largest profit increases of more than €500 per cow were observed in farms where below-average stocking densities (<2 LU/ha) and together with below-average cow longevity (<3 lactations per cow) were prevalent. In contrast, farms with stocking densities >2 LU/ha and high average cow longevity (>5 lactations per cow) were most often found to have profit gains in the range of €0 to €30 per cow.

The economic impact of the change in genetic level induced by sexed semen and beef semen use (genetic return) ranged from €0 to €21 per cow, with an average genetic return of €4.98 per cow (median €2.16 per cow) among the sample population. Changes in costs linked to dystocia ranged from €3.80 to €12.45 per cow, with an average change of €0.31 per cow.

DISCUSSION

Results

Our results imply that a profit-maximizing utilization of crossbreeding and sexed semen among North Rhine-Westphalian dairy farms could improve profits

from €0 to €568 per cow per year. We found that almost half of the simulated farm population could increase their profits by using female-sexed dairy semen on heifers for replacement heifer production and by using beef semen on cows to some extent. However, potential economic gain of sexed semen and crossbreeding utilization, as indicated in our results, varied greatly depending on individual farm endowments such as stocking density and average cow longevity, among other factors. In line with the findings of McCulloch et al. (2013), the strategy of producing excess heifers for sale with the use of sexed dairy semen was found to be profit-maximizing, although only for farms with below-average stocking densities (<1.5 LU/ha). Especially when a high grassland share was present, rearing excess heifers was a profitable opportunity for these farms, as often no production alternative for grassland was present. The overall highest potential economic gains of up to €568 per cow were observed when below-average stocking density, an average cow longevity <3 lactations per cow, high heifer prices, and favorable sexed semen parameters (high conception rates and accuracy of sexed semen) were jointly present. For these farms, using sexed semen on all heifers as well as all cows was found to be most profitable, confirming the findings of Cottle et al. (2018) for such types of farms.

Farms with higher average cow longevity were generally rearing excess heifers even before the introduction of sexed semen into the model, and thus had a smaller profit gain from the new technology. Given increased profits per cow, many of these farms would have potentially invested in new cattle housing to further expand their herd in the model. However, as stated in the previous sections, investments in new cattle housing were disabled to depict the rather short-term effects of sexed semen and crossbreeding usage.

With increasing stocking densities, feed competition among animal groups within the farm increased. As buying of roughages from the market was disallowed in the analysis, farms that could barely sustain their cow herd size due to limited own fodder production had little incentive to produce excess heifers. To rear excess heifers, these farms would have needed to reduce their cow herd, increasing the marginal production costs of heifers by the opportunity costs of the cows that could have been fed instead. Farms with stocking densities >2 LU/ha and milk yields >10,000 kg of ECM were therefore rarely found to produce more heifers than required for their own replacements. These findings support the results of Ettema et al. (2017), where the profitability of excess heifers was largely determined by additional heifer-rearing costs.

Farms with higher stocking densities were often found to be using beef semen to produce crossbred

Figure 4. Simulated profit increase (€/cow) induced by the profit maximal use of sexed dairy semen and sexed/conventional beef semen among the North Rhine-Westphalian dairy farm population. Each dot represents a farm in the sample population. LU = livestock units.

calves instead of excess heifers. As the crossbred calves were assumed to be sold right after birth, these animals were not competing for additional feed with any additional heifers raised on farm. This way, fodder could be valorized by the cow herd with higher marginal returns.

Farms with average cow longevity well above the mean (>5 lactations per cow) and limited roughage availability (stocking densities >2 LU/ha) showed the highest beef semen uptake shares of 60 to 80%. Within this particular group, farms exposed to higher crossbred calf prices ($>€200$ /head) and sexed semen conception rates $>90\%$ of conventional semen conception rates were particularly likely to show high rates of sexed beef semen usage. Due to the relatively low replacement rates induced by the high average cow longevity, these farms were able to take specific advantage of crossbred calf price premiums. In scenarios with high prices for crossbred calves, farms with limited fodder availability (stocking densities >2 LU/ha) were generally producing their replacement animals by using sexed semen on the genetically superior heifers to be able to produce more crossbred calves. Farms with average cow longevity <5 lactations per cow together with stocking densities >2 LU/ha were most often using a similar breeding strategy. However, due to their higher demand for female calves for replacements, the average beef semen uptake

of these farms was clearly lower. Among the farms that used beef semen to produce crossbred calves, sexed beef semen was found to play only a minor role. On average, only 3.3% of all heifers and 0.1% of all cows were inseminated using sexed beef semen in the part of the sample that used beef semen.

As the change in genetic level due to sexed semen and beef semen use was simulated based on the results outlined by Ettema et al. (2017), the range of genetic returns from €0 to €21 per cow reflected their findings. On average, the genetic return made up for 13.10% of the sexed semen and beef semen induced profit gain. These results indicate the importance of incorporating genetic return when assessing the profitability of sexed semen and beef semen use.

Crossbreeding remained profitable for almost half of the farms within the sample population to some extent, even when increased dystocia risk and related costs were considered. However, as farms were able to reduce dystocia risk by using female-sexed dairy semen (especially on heifers), the increased dystocia risk when using beef semen on cows was partially offset.

Despite the presented findings, sexed semen and crossbreeding played a minor role in North Rhine-Westphalian dairy production systems at the time of writing. As noted previously, sexed semen was used in

only 6% of all Holstein heifer inseminations in Germany in 2018 (Arbeitsgemeinschaft Deutscher Rinderzüchter, 2018). Figures for multiparous cow inseminations with sexed semen and beef semen inseminations were not available. Using sexed semen on favorable heifers and cows for replacements, and beef semen on the remainder of the herd has been proposed in a series of agricultural magazine articles in Germany (Elite Magazin, 2009; Thomsen, 2016). The discrepancy between its profitability found in research and the limited uptake in practice requires further research; for instance, considering additional transaction costs for marketing crossbred calves or looking into differences between perceived risks by farmers and the risks assumed in studies.

Methodological Approach

Our approach extends the existing literature in multiple aspects. First, we applied a highly detailed farm-scale model instead of a model at process scale to consider the effects of varying stocking densities. Second, we drew on empirical distributions for the dairy farm population in our study region, and, third, we performed systematic sensitivity analysis as well as post-model statistical analysis. The approach could be seen as a more general methodology by which to estimate potential adaptation rates in a farm population for a technology for which technological parameters and related costs and benefits can be derived from literature but sufficient farm observations on adaptation are (not yet) available.

Using a holistic single-farm optimization model for the analysis has a set of advantages over simulation approaches where fewer variables are endogenous. The FarmDyn model endogenously optimizes multiple decision variables simultaneously. These variables include herd entry and exit dates, fodder production and use of concentrates, grassland management, manure storage and management, allocation of labor to cash crops and herd management, stable and machinery utilization, as well as inputs required for crop production. Instead of a simplified simulation approach, where levels of (certain) decision variables (e.g., feed uses, heifer breeding strategies, and crop allocation) are predetermined in scenarios, we simulated profit-maximizing levels. The resulting profit-maximizing strategies for crossbreeding and sexed semen therefore show the full potential of the considered options, because they incorporate the complexity of the decision on the whole-farm level. Although previous studies reported on important drivers of sexed semen (and partially beef semen) adoption for specific farm types given fixed farm endowments (McCulloch et al., 2013; Ettema et al., 2017; Cottle et

al., 2018), our approach highlights the importance of studying the whole variety of farms in a population.

However, considering more endogenous variables comes at the price of a more complex model, introducing more assumptions and possibly uncertain parameters. It also might mean reducing model detail in other aspects. For instance, in an effort to reduce complexity FarmDyn only models an average animal in each herd, instead of individual animals of a certain genetic level.

As previously stated, empirical distributions for parameters not present in the Farm Structure Survey were not available. For reasons of simplicity, but without loss of generality, uniform distributions without correlations were assumed for these input parameters. Recent data by KTBL (2018) report a spread of the average cow longevity between 1.7 and 6.6 lactations per cow (see Table 1), which results in an ingoing sample mean of 4.15 lactations. This is higher than the average of 2.7 lactations stated by Römer et al. (2009), which could not be incorporated in the LHS approach because of missing information on the underlying distribution. Upon availability, future research should incorporate observed distributions for all endogenous model parameters to better reflect the underlying statistical population.

The combination of the LHS with the economic model endogenously removes draws from the LHS that are implausible from an economic viewpoint. Specifically, for 13.2% of the farms in the LHS sample, the economic model found that herding cattle was not profitable. In these cases, no cow herd and related profit maximal management choices such as rates of sexed semen use can be observed. Not surprisingly, many such dropped observations comprise farms with quite high replacement rates. The analyzed sample with positive profits only still contains the entire input range of the replacement rates. However, the average cow longevity increased from 4.15 to 4.46 lactations in the usable observations, matching a replacement rate of approximately 22%.

Under profit maximization, the model will switch to production alternatives compared with the status quo even if the additional profit gain is marginal. To give an example, the model would choose to produce crossbred calves as soon as their relative profitability surpasses that of purebred calves, as long as other constraints (e.g., required replacement heifers, available housing places) are met. However, in these cases where one production option is found to be only slightly more profitable than another, farmers may decide to remain with their “traditional” production portfolio because of personal preference, additional hidden costs, or other unknown factors. As the average sexed semen and crossbreeding induced relative profit increase was found

to be €79.42/cow and year, the effect can be seen as substantial enough to be considered an advantageous production option.

With the relatively high simulated share of crossbred animals produced within the farm population, feedback of the supply increase on the producer price of crossbred calves, as discussed by De Vries et al. (2008), could be expected. That feedback cannot be considered in FarmDyn, as a supply-side model characterized by exogenous input and output prices. Here, also the systematic sensitivity analysis (meta-model) does not help. Market models such as (partial) equilibrium models incorporate such market feedback by design but miss the detailed depiction of technical production processes required by the present study.

CONCLUSIONS

The profit-maximizing sexed semen and beef semen (for crossbreeding) utilization of North Rhine-Westphalian dairy farms was found to be highly heterogeneous. Farms with lower stocking densities maximized profits using sexed semen to produce excess heifers for sale, whereas farms with higher stocking densities instead produced crossbred calves for sale and used sexed semen on heifers to produce replacement animals. Furthermore, sexed semen and crossbreeding usage was found to depend on farm characteristics such as average cow longevity, sexed semen-related parameters such as sexed semen conception rate and accuracy, as well as market factors such as the prices of replacement heifers and crossbred calves. Because of continuous improvements to sex-sorting technology and the economic benefits found in our analysis, sexed semen adoption is likely to increase further among the study population. Our results highlight the importance of studying a whole variety of farms in a study population, because driving factors for sexed semen and beef semen adoption were shown to differ substantially among farms.

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