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Expanding the dairy herd in pasture-based systems: The role of sexed semen within alternative breeding strategies

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ABSTRACT

A simulation model was developed to determine the effects of sexed semen use in heifers and lactating cows on replacement heifer numbers and rate of herd expansion in a seasonal dairy production system. Five separate artificial insemination (AI) protocols were established according to the type of semen used: (1) conventional frozen-thawed semen (CONV); (2) sexed semen in heifers and conventional semen used in cows (SS-HEIFER); (3) sexed semen in heifers and a targeted group of cows (body condition score ≥3 and calved ≥63 d), with conventional semen used in the remainder of cows (SS-CONV); (4) sexed semen in heifers and a targeted group of cows, with conventional semen in the remainder of cows for the first AI and conventional beef semen used for the second AI (SS-BEEF); or (5) sexed semen in heifers and a targeted group of cows, with conventional semen in the remainder of cows for the first AI and short gestation length semen used for the second AI (SS-SGL). Each AI protocol was assessed under 3 scenarios of sexed semen conception rate (SS-CR): 100, 94, and 87% relative to that of conventional semen. Artificial insemination was used on heifers for the first 3 wk and on cows for the first 6 wk of the 12-wk breeding season. The initial herd size was 100 cows, and all available replacement heifers were retained to facilitate herd expansion, up to a maximum herd size of 300 cows. Once maximum herd size was reached, all excess heifer calves were sold at 1 mo old. All capital expenditure associated with expansion was financed with a 15-yr loan. Each AI protocol was evaluated in terms of annual farm profit, annual cash flow, and total discounted net profit. The SS-CONV protocol generated more replacement heifers than all other AI protocols, facilitating faster expansion, and reached maximum herd size in yr 9, 9, and 10 for 100, 94, and 87% SS-CR, respectively. All AI protocols, except SS-BEEF and SS-SGL at 87% SS-CR, reached maximum herd size within the 15-yr period. Negative profit margins were experienced for SS-CONV in the first 5, 4, and 3 yr of expansion for 100, 94, and 87% SS-CR, respectively. Total discounted net profit was greater in all sexed semen AI protocols compared with CONV. This study demonstrated that, for each SS-CR, the greatest rate of expansion is achieved when using sexed and conventional semen (SS-CONV). The combined use of sexed semen and beef (SS-BEEF) or SGL (SS-SGL) semen resulted in greater discounted net profit at 100, 94, and 87% SS-CR compared with CONV, but a similar net worth change at 87% SS-CR due to a lower inventory change because SS-BEEF and SS-SGL reached maximum herd size within 15 yr.
Key words: sexed semen, herd expansion, economics, simulation model, dairy, beef

INTRODUCTION

Since the 1980s, sperm sorting via flow cytometry has been the most successful method available for sex selection, and the sorting process has been extensively described (Garner and Seidel, 2008; Schenk et al., 2009; Seidel, 2013). Previously, sexed semen has achieved conception rates that were 70 to 80% of those achieved with conventional semen (DeJarnette et al., 2009, 2010; Norman et al., 2010). Recent advancements in sorting technology have reduced the time lag during processing and lessened some of the damage incurred during sorting, such as that due to pH and temperature fluctuations. Field studies in Ireland (frozen-thawed sexed semen) and New Zealand (fresh sexed semen) reported that mean conception rates for sexed semen were 87 and 94% of those achieved with conventional semen, respectively (Butler et al., 2014; Xu, 2014). A later field study conducted in Germany used a frozen sexed semen treatment at 4×10^6 sperm per dose and achieved non-return rates equal to those achieved with conventional semen (Vishwanath, 2015). If conception rates with sexed semen could equal those of conventional semen, the economics of sexed semen usage would be markedly improved. Global demand for milk and meat protein is forecast to increase in the coming decades (Alexandratos and Bruinsma, 2012), which will necessitate

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both greater numbers of dairy cows and more efficient beef production from the dairy herd. Sexed semen may be a useful technology to rapidly increase dairy heifer calf inventory, while also facilitating increased output of crossbred beef calves.

A field study conducted in Ireland in 2013 indicated that BCS and the number of DIM have a significant effect on conception rate in dairy cows inseminated with sexed semen. Cows that had a BCS ≥3 (measured on a 1–5 scale; Edmonson et al., 1989) and were calved ≥63 d had greater conception rates and were more suitable for sexed semen use than thinner cows that were calved for less time (Butler et al., 2014). If sexed semen use is targeted on the highest fertility animals in a herd, all necessary replacement animals could potentially be conceived in the first 3-wk of the breeding season, despite fertility reductions, allowing farmers to use easy-calving, nondairy sires for the second round of AI (i.e., wk 4–6 of the breeding season). For example, it would be possible to switch to conventional beef semen or short gestation length (**SGL**) semen. Calves from SGL semen have a low sale value and are not suitable as replacement heifers, but calving interval can be reduced by 5 to 10 d on average (LIC, 2016), increasing both 6-wk calving rate and lactation length. Systems in which both heifers and a targeted group of cows are inseminated with sexed semen have previously been shown to result in greater profitability (Hutchinson et al., 2013b; McCullock et al., 2013). The objective of this study was to model alternative strategies for the use of sexed semen in heifers and lactating cows in seasonal pasture-based dairy production systems and to determine the potential effects on rate of expansion and farm profitability.

MATERIALS AND METHODS

Fertility Model

A model was developed using Microsoft Excel (Microsoft Corp., Redmond, WA) to simulate the reproductive performance of a hypothetical spring-calving Holstein-Friesian dairy herd over a 15-yr period (Hutchinson et al., 2013a,b). The effect of using sexed semen or conventional semen in heifers and lactating cows on the number of heifers available for incorporation into the lactating herd was included in the model. Five separate AI protocols were established according to reproductive management related to sexed and conventional semen use: (1) only conventional frozen-thawed dairy semen used for the first AI in heifers and the first 6 wk of the breeding season in cows (**CONV**); (2) sexed semen used for the first AI in heifers and conventional semen for the first 6 wk of the breeding season in lactating cows (**SS-HEIFER**); (3) sexed semen used for the first AI in heifers and the first 3 wk of the breeding season in targeted cows (i.e., those with BCS ≥3 and DIM ≥63 d), with conventional semen used in the remaining cows, and conventional dairy semen in all cows in the second 3 wk of the breeding season (**SS-CONV**); (4) sexed semen used for the first AI in heifers and first 3 wk of the breeding season in targeted cows (as in SS-CONV), with conventional easy-calving, early maturing beef semen used in the second 3 wk of the breeding season in all cows (**SS-BEEF**); or (5) sexed semen used for the first AI in heifers and first 3 wk of the breeding season in targeted cows (as in SS-CONV), with SGL semen used in the second 3 wk of the breeding season in all cows (**SS-SGL**). After the period of AI use, all empty cows and heifers were bred to natural service during a breeding period of 6 and 9 wk, respectively. Each AI protocol was simulated under 3 scenarios of sexed semen conception rate relative to conventional semen (**SS-CR**): 100, 94, and 87% SS-CR (Table 1). The values for SS-CR were based on data from studies using sexed semen in heifers in Ireland and Germany (Butler et al., 2014; Vishwanath, 2015) and lactating cows in Switzerland, Ireland, and New Zealand (Bodmer et al., 2005; Butler et al., 2014; Xu, 2014).

Reproductive Performance of Heifers

The 12-wk breeding season, commencing on April 25 in each simulation year, was divided into four 3-wk periods (Hutchinson et al., 2013a,b). The submission rates (**SR**, proportion of heifers intended to be bred that were inseminated within a 3-wk period) and conception rates (**CR**, proportion of heifers conceiving to a given insemination) of the heifers are shown in Table 2. Heifers were inseminated following spontaneous estrus; use of synchronization for the first insemination was not included in the model. All heifers that did not conceive in the first 3-wk period were bred by natural service for the remainder of the breeding season. The heifers that conceived were attributed a conception date that was the median date of that 3-wk period. The mean calving date for the following year was then calculated as the mean conception date plus 282 d. All heifers that calved were included in the model for the lactating herd of their respective treatment the following year. The model assumes that all replacement heifers were eligible for breeding by approximately 14 to 16 mo of age and subsequently calved for the first time at approximately 23 to 25 mo of age. Dairy heifers born to cows within the first 6 wk and to heifers within the first 3 wk of the calving period were retained as dairy replacements.

Table 1. Reproductive performance of lactating cows in a simulated herd (Herlihy et al., 2011; Macmillan, 2012), when expanding from 100 to 300 cows using conventional frozen-thawed or sexed semen, assuming 3 different sexed semen conception rates relative to conventional semen (SS-CR): 100, 94, and 87% SS-CR

					All semen types	
DIM at insemination	Conventional frozen-thawed	Sexed (100% SS-CR)	Sexed (94% SS-CR)	Sexed (87% SS-CR)	SR[1]	Embryo survival
>83	0.60	0.60	0.56	0.52	0.90	0.98
63–82	0.55	0.55	0.52	0.48	0.85	0.95
42–62	0.48	0.48	0.45	0.42	0.78	0.93
21–41	0.37	0.37	0.35	0.32	0.67	0.91
<21	0.20	0.20	0.19	0.17	0.20	0.90

[1]Submission rate (SR) = proportions of cows intended to be bred that are inseminated within a 21-d period.

Reproductive Performance of Lactating Cows

The values used for SR, CR, and embryo survival for all semen types are shown in Table 1. Submission rates, CR, and embryo survival rates in the model vary according to the cow's DIM during the breeding season, and these values were derived from 2 large field studies in pasture-based systems using conventional semen that indicated poorer reproductive performance in cows with short intervals from calving to planned start of mating (Herlihy et al., 2011; Macmillan, 2012). Submission rates and embryo survival rates did not differ with semen type used. The model for cows was similar to the heifer model, and was based on a 12-wk breeding season split into four 3-wk periods. The DIM at each stage of the breeding season was calculated from calving date until the first day of each 3-wk period. The values for SR, CR, and embryo survival (Table 1) were applied at herd level to the proportion of cows not pregnant in each of the four 3-wk periods during the breeding season. All cows that did not conceive in a given 3-wk period were eligible for insemination in the next 3-wk period. Mean calving dates were calculated using the same method outlined in the heifer reproductive performance model, with the exception of cows that conceived following insemination with SGL semen and calved 9 d earlier than the respective mean calving date. The calculated calving dates were then used in the model for the following year to calculate DIM at the date of planned breeding.

The number of cows that underwent embryo loss was calculated as a proportion of the cows that conceived in each 3-wk period, and the number varied according to DIM at insemination. When embryo loss occurred, these cows were not eligible for re-insemination until 6 wk after the initial successful insemination. Cows were not re-inseminated if embryo loss occurred after the end of the 12-wk breeding season or if the initial successful insemination occurred within 6 wk of the end of the 12-wk breeding season.

Mortality and Survival

Animals that did not conceive during the 12-wk breeding season were culled from the herd. Mortality in the lactating herd was assumed to be 2%, and voluntary culling in the lactating herd was assumed to be 8% of the cows that remained in the herd following involuntary culling (Hutchinson et al., 2013a,b). These figures were applied to each herd at year-end for every year of the simulation. Heifer calf survival to 1 mo of age was assumed to be 96% of successful conceptions (DAFM, 2014), and heifer calf survival to breeding at approximately 14 mo of age was assumed to be 96%

Table 2. Reproductive performance of heifers in a simulated herd (Hutchinson et al., 2013a,b), when expanding from 100 to 300 cows using conventional frozen-thawed or sexed semen, assuming 3 different sexed semen conception rates relative to conventional semen (SS-CR): 100, 94, and 87% SS-CR

	Semen type			
Item[1]	Conventional frozen-thawed	Sexed (100% SS-CR)	Sexed (94% SS-CR)	Sexed (87% SS-CR)
First and second insemination SR	0.90	0.90	0.90	0.90
First and second insemination CR	0.70	0.70	0.66	0.61
Third and fourth insemination SR	0.75	0.75	0.75	0.75
Third and fourth insemination CR	0.30	0.30	0.35	0.40

[1]Submission rate (SR) = proportions of heifers intended to be bred that are inseminated within a 21-d period; conception rate (CR) = proportion of heifers pregnant to a given insemination.

of successful calf survival beyond 1 mo of age (DAFM, 2014).

Semen Costs

Semen costs were established by surveying the main cattle breeding companies in Ireland, and they reflect current market prices. The price per straw of frozen-thawed conventional semen from a dairy sire, sexed semen from a dairy sire, and conventional early-maturing beef semen were €18, €38, and €10, respectively (ICBF, 2015a,b). Straws containing SGL semen are not currently available on the Irish market, and the price per straw was assumed to be €10, based on the New Zealand price differential between SGL and conventional dairy semen. It was assumed that all inseminations were carried out by AI technicians. An insemination fee of €16 per cow for the first service was allocated for each of the AI protocols; no insemination fee was charged for repeat heats, in accordance with current practice in the cattle breeding industry in Ireland.

Farm Demographics

Base herd size was fixed at 100 cows for each AI protocol in yr 1 of the simulation. One scenario of land availability was examined, with limited land available for expansion, permitting a maximum herd size of 300 cows; hence, herd expansion was limited to a 200% increase in cow numbers. Heifer calves born on farm within the first 6 wk of the calving period were kept as replacements to expand the herd. The use of sexed semen was continued after the point at which maximum herd size was reached. However, herd size was maintained at 300 cows, and all excess heifer calves were sold at 1 mo of age.

Milk Production

Milk production per cow was dependent on parity, and full yield potential was reached in the fourth lactation. Based on Irish data, the proportion of milk production was 0.75, 0.92, and 0.98 of fourth lactation yield for first, second, and third parity cows, respectively (Hutchinson et al., 2013a,b). Milk production per cow increased by 1%/yr from a starting point of 5,750 kg/cow per year for fourth-lactation animals in yr 1 of the simulation. Milk constituents also increased annually with a rate of increase of 0.5%/yr for milk fat content and 0.3%/yr for milk protein content, from a starting point of 39.9 g/kg fat content and 34.3 g/kg protein in yr 1 of the simulation. The increased levels of milk and milk constituent production represent the annual rate of gain in milk production and were calculated using historical Irish milk production data (CSO, 2016b).

Financing Expansion

The investment required to finance herd expansion, using Irish data, is outlined in Table 3. A value of €1,500 per cow was attributed in yr 1 of the simulation to represent the cost of animal housing and facilities currently in place on the farm (Hutchinson et al., 2013a,b). It was assumed that for increases in herd size up to 150 cows an investment of €3,000 per cow was required, with further herd expansion requiring an investment of €2,000 per cow (Hutchinson et al., 2013a,b). This difference was included to reflect the nonlinear investment costs associated with expansion and the increased cost associated with lower levels of expansion. The investment was financed with a 15-yr loan and depreciated over a 15-yr period. To account for the investment happening in stages on a farm, all investment required up to yr 7 was carried out in yr 1 and the increased investment required between yr 7 and 15 was carried out in yr 7, with the annual loan repayment structures detailed in Supplementary Table S1 (http://dx.doi.org/10.3168/jds.2015-10378).

Economic Analysis

The Moorepark Dairy Systems Model (**MDSM**; Shalloo et al., 2004), a stochastic budgetary simulation model, was used to simulate a model farm integrating biological data for the different herds generated by each AI protocol. The model was used to quantify the

Table 3. Investment required to fund herd expansion from 100 to 300 cows in a simulated herd using conventional (CONV), sexed (in heifers only; SS-HEIFER), sexed plus conventional (SS-CONV), sexed plus beef (SS-BEEF), or sexed plus short gestation length semen (SS-SGL) in heifers and lactating cows, assuming 3 different sexed semen conception rates relative to conventional semen (SS-CR): 100, 94, and 87% SS-CR

SS-CR (%)	Herd	Year 1 (€)	Year 7 (€)
—	CONV	336,237	265,278
100 (%)	SS-HEIFER	459,004	185,675
	SS-CONV	591,608	97,953
	SS-BEEF	381,722	237,198
	SS-SGL	381,722	237,198
94 (%)	SS-HEIFER	430,556	204,093
	SS-CONV	539,410	133,035
	SS-BEEF	335,497	267,533
	SS-SGL	335,497	267,533
87 (%)	SS-HEIFER	398,617	227,039
	SS-CONV	482,499	171,555
	SS-BEEF	286,018	161,697
	SS-SGL	286,018	161,697

economic implications of sexed semen use on farm profitability under different usage distributions and sensitivities. The model can simulate any combination of differing calving patterns. In this analysis, differences in calving date were simulated based on outputs from the reproduction model. These differences affected the milk production profile and feed budgets of the different scenarios modeled. The key herd default parameters used in the model farm are determined using recent Irish data (Hutchinson et al., 2013a,b; Teagasc, 2014) and are shown in Table 4. All male and surplus female calves were sold at 1 mo of age. Replacement females were contract reared, leaving the farm at 1 mo of age. The final conception rates of the heifers differed under the different semen treatments, which meant that the net cost of replacement heifers to the farm differed with type of semen used. The reduced fertility of sexed semen compared with conventional semen increased heifer rearing costs to €1,558 and €1,570 for 94 and 87% SS-CR, respectively, compared with €1,545 for CONV and 100% SS-CR (Shalloo et al., 2014). This increase was because a greater number of heifers needed to be reared to generate the same number of heifers calving down in the reduced fertility sexed semen options compared with conventional semen and 100% SS-CR. The default owned farm size was 60 ha (Table 4). Land area was treated as an opportunity cost; land was leased out when not required for on-farm feeding of animals in the early years of the simulation, or rented when required due to increased herd size in subsequent years.

The MDSM integrates animal inventory and valuation, milk production, feed requirement, land and labor utilization, and economic analysis. The overall feed requirement was calculated by the MDSM to meet the net energy requirements for maintenance, milk production, and BW change across lactation (Jarrige, 1989). Variable costs (fertilizer, contractor charges, medical and veterinarian, silage, and reseeding), fixed costs (machinery maintenance and running costs, farm maintenance, car, telephone, electricity, and insurance), and sales receipts (milk, cull cow and calf) were based on current prices (Teagasc, 2014). The AI protocols were compared at a milk price of €0.27/L assuming 33.0 g/kg protein and 36.0 g/kg fat with a relative price ratio of 1:2 for fat to protein.

Table 4. Key parameters used in the simulation, for a simulated herd expanding from 100 to 300 cows, as extracted from recent Irish data (Hutchinson et al., 2013a,b; Teagasc, 2014)

Item	Value
Owned farm size (ha)	60
Reference fat (g/L)	36
Price ratio protein to fat	2
Labor costs (€/labor unit)	22,860
Gross milk price (€/L)	0.27
Reference cull cow price (€)	400
Reference male calf price (€)	85
Reference heifer calf price (€)	350
Concentrate costs (€/t)	250
Opportunity cost of land (€/ha)	250

Annual profit, cash flow, and discounted net profit over the 15-yr period were included in the analysis when defining the optimum strategy for evaluating the differing semen options. Discounted net profit is the financial reward resulting from gross output exceeding the farm direct and operational expenses on an annual time step and considers the time value of profits realized (McDonald et al., 2013). Because the different options evaluated resulted in different profitability levels over the 15 yr of the simulation, the discounted farm profitability allowed a direct comparison between AI protocols, taking into account the different periods of maximum profitability in each of the options. An annual discount rate of 2% was included in this analysis based on historical inflation (CSO, 2016a). Discounted net profit combined with the value of the inventory change was used to calculate net worth change over the 15-yr period of the simulation for each AI protocol under different semen usage scenarios. Milk price sensitivity analysis was performed to examine the financial viability of the various AI protocols under 3 SS-CR scenarios at €0.22/L and €0.32/L, which represent recent fluctuations in milk price (Donnellan et al., 2015). Sensitivity analysis of the sale price of calves sold for beef (male dairy and all crossbred beef calves) was performed at ±€30 for each AI protocol under 3 SS-CR scenarios. The main equations used in the simulation model to calculate discounted net profit and net worth change were as follows:

$$\text{Cow no.} = [\text{cow no. in year } X - (\text{culled cows} + \text{cow deaths})] + (\text{Hf} - \text{Hf deaths}), \quad [1]$$

$$\text{Gross output} = (\text{cow no.} \times \text{milk yield} \times \text{milk price}) + \text{livestock sales}, \quad [2]$$

$$\text{Discounted net profit} = \text{gross output} - (\text{variable} + \text{fixed costs}), \quad [3]$$

$$\text{Net worth change} = \text{discounted net profit} + \text{inventory change}, \quad [4]$$

where cow no. = cow numbers; X = 1 to 15, Hf = number of heifers born 2 yr previous to X, now eligible for breeding; livestock sales = culled cows, excess heifer and male dairy calves, and crossbred beef calves; and inventory change = change in animal assets from yr 1 to 15.

RESULTS

Herd Expansion

The key physical outputs from the 5 AI protocols modeled over the 15-yr simulation period under 3 SS-CR scenarios are summarized in Figure 1. SS-CONV reached maximum herd size of 300 cows in yr 9 for 100 and 94% SS-CR and yr 10 for 87% SS-CR, 2 yr earlier than SS-HEIFER for each SS-CR. SS-BEEF and SS-SGL reached maximum herd size in yr 13 for 100% SS-CR, yr 15 for 94% SS-CR (parallel with CONV), but reached a maximum herd size of 230 cows at the end of the 15-yr period for 87% SS-CR. The number of heifer calves generated by each AI protocol followed a similar pattern, with SS-CONV generating the greatest number of heifer calves, followed by SS-HEIFER, with CONV producing the fewest heifer calves.

Monthly Proportion of Cows Calving

The proportions of the herd calving in each calendar month during the 3-mo spring calving period for each AI protocol at 100, 94, and 87% SS-CR are summarized in Supplementary Figure S1 (http://dx.doi.org/10.3168/jds.2015-10378). Group SS-SGL achieved the greatest proportion of the herd calving in February (at the start of the calving period) for all years, regardless of SS-CR. For all other sexed semen AI protocols at 100 and 94% SS-CR, the proportion of cows calving in February was similar to that of CONV, despite a faster rate of herd expansion. At 87% SS-CR, the proportion of cows calving in March and April increased during the 15-yr simulation period for SS-CONV and SS-BEEF compared with CONV because of the reduced fertility of sexed semen.

Annual Profit Margins and Cash Flow

Annual profit and cash flow figures for the 5 AI protocols, modeled over the 15-yr period at 100, 94, and 87% SS-CR are summarized in Tables 5, 6, and 7, respectively. CONV maintained positive profit margins and cash flow for every year of the simulation. SS-CONV generated negative profit margins in the first 5 yr, first 4 yr, and yr 3 of the simulation for 100, 94, and 87% SS-CR, respectively, with the most negative profit margin of −€23,325 occurring in yr 3 at 100% SS-CR. Cash flows were also negative in yr 3 in SS-CONV at 100 and 94% SS-CR. SS-HEIFER generated negative profit margins in yr 3 at 100% SS-CR but maintained positive cash flow during the entire 15-yr period. At 94 and 87% SS-CR, SS-HEIFER maintained positive profit margins and cash flow for the entire simulation period. At all SS-CR, CONV, SS-BEEF, and SS-SGL maintained positive profit and cash flow during the simulation and recorded greater profit and cash flow in yr 1 to 6 compared with those of SS-CONV and SS-HEIFER. At 94 and 87% SS-CR, initial profit and cash flow were greatest in SS-BEEF and SS-SGL because of a slower rate of expansion; however, this advantage had diminished by yr 7 and yr 10 for 94 and 87% SS-CR, respectively.

Discounted Net Profit and Net Worth Change

Discounted net profit, inventory change, and net worth change are summarized in Table 8. Discounted net profit was greater in all sexed semen AI protocols compared with CONV. In each SS-CR scenario, SS-CONV generated the greatest discounted net profit, followed by SS-BEEF, SS-SGL, and SS-HEIFER, with the exception of 94% SS-CR in which SS-HEIFER generated the second greatest discounted net profit. The value of inventory change was relatively equal for all AI protocols regardless of SS-CR (range: €304,880–€308,960), with the exception of SS-BEEF and SS-SGL at 87% SS-CR, which did not expand to a 300 cow herd within the 15-yr simulation period and hence reported a lower inventory change (€216,840). SS-CONV reported the greatest net worth change within each SS-CR scenario, and the lowest net worth change was reported by CONV within the 100 and 94% SS-CR scenarios and SS-SGL at 87% SS-CR.

Sensitivity Analysis

The effects of variations in milk and beef sale prices on total profit and median annual profit are summarized in Tables 9 and 10. Total profit and median annual profit were positive for each of the AI protocols under all SS-CR scenarios at a milk price of €0.32/L, with the greatest profit achieved in SS-CONV for each SS-CR. When milk prices were €0.22/L all AI protocols, with the exception of SS-BEEF at 100 and 87% SS-CR and SS-SGL at 87% SS-CR, reported negative figures for total profit (i.e., losses). These losses were greatest in SS-CONV at 94 and 87% SS-CR and in CONV.

Total profit and median annual profit were positive for each of the AI protocols under all SS-CR scenarios when the sale price of calves sold for beef production varied. The greatest profit was achieved in SS-CONV for each SS-CR scenario, regardless of sale price, with CONV reporting a lower total profit compared with sexed semen AI protocols.

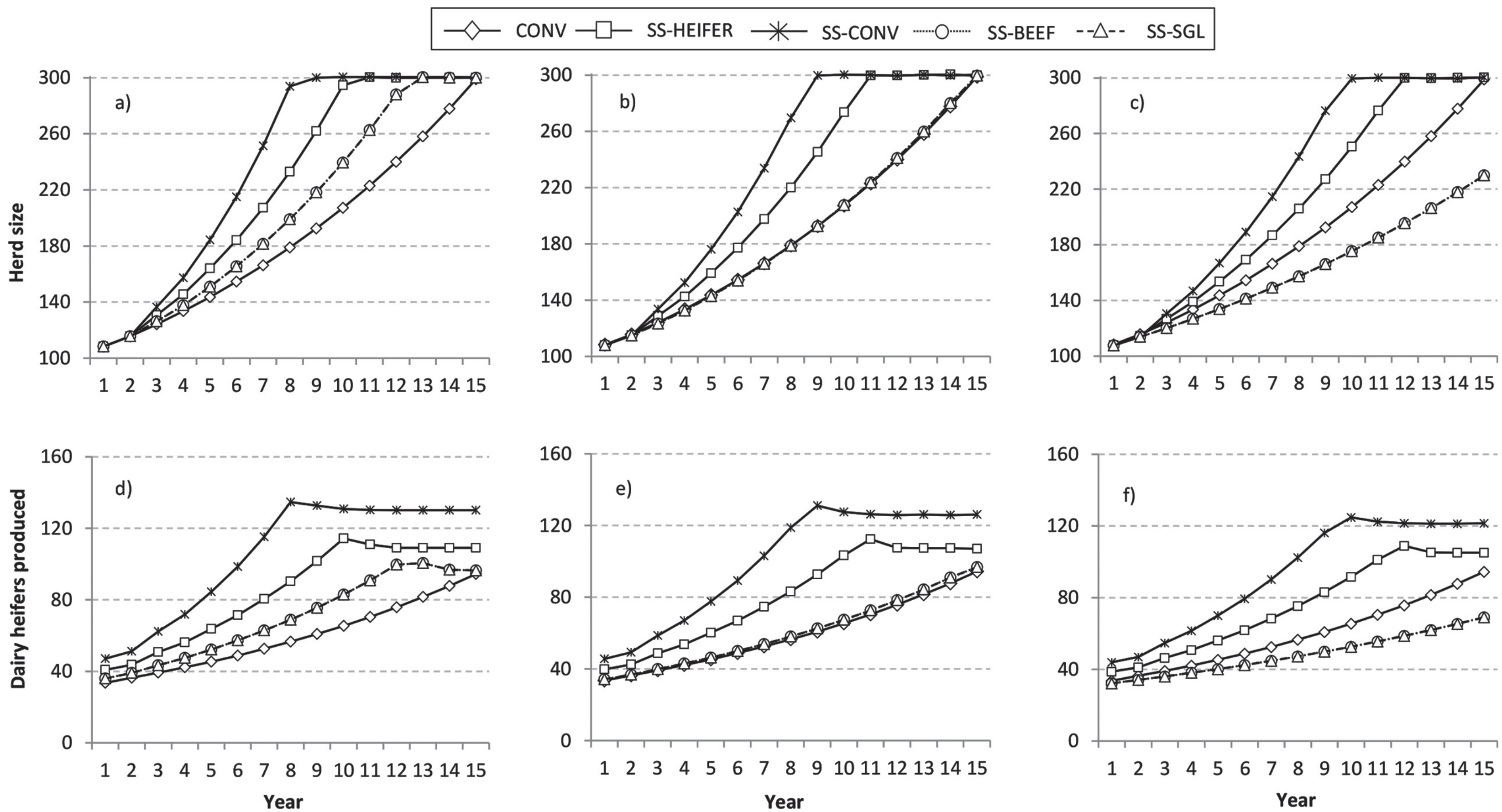

Figure 1. Herd size (upper panel) and number of heifer calves born in the first 6 wk surviving to 1 mo old (lower panel) in a simulated herd expanding from 100 to 300 cows using conventional (CONV), sexed (in heifers only; SS-HEIFER), sexed plus conventional (SS-CONV), sexed plus beef (SS-BEEF), or sexed plus short gestation length semen (SS-SGL) in heifers and lactating cows, assuming the conception rates achieved with sexed semen are 100 (a, d), 94 (b, e), and 87% (c, f) of conventional semen.

Table 5. Annual profit and cash flow from a simulated herd expanding from 100 to 300 cows using conventional (CONV), sexed in heifers only (SS-HEIFER), sexed plus conventional (SS-CONV), sexed plus beef (SS-BEEF), or sexed plus short gestation length semen (SS-SGL) in heifers and lactating cows, assuming the conception rates achieved with sexed semen are 100% of conventional semen

	CONV		SS-HEIFER		SS-CONV		SS-BEEF		SS-SGL	
Year	Profit (€)	Cash flow (€)	Profit (€)	Cash flow (€)	Profit (€)	Cash flow (€)	Profit (€)	Cash flow (€)	Profit (€)	Cash flow (€)
1	16,863	26,923	4,506	17,272	−10,326	5,364	17,036	28,099	16,256	27,319
2	15,503	24,738	3,462	15,101	−10,724	3,514	16,242	26,369	15,407	25,534
3	18,337	26,702	−1,834	8,618	−23,325	−10,619	16,763	25,900	15,883	25,021
4	22,479	29,925	8,285	17,483	−9,259	1,831	23,029	31,125	22,078	30,173
5	27,136	33,613	12,636	20,511	−4,177	5,207	28,127	35,121	27,105	34,100
6	33,210	38,664	23,226	29,705	9,211	16,796	36,307	42,141	35,201	41,035
7	36,564	6,122	42,272	11,347	45,456	14,165	46,182	15,435	44,987	14,240
8	16,249	12,309	23,896	22,325	28,117	29,152	27,240	24,140	25,947	22,846
9	25,414	18,906	38,085	33,919	105,000	103,418	39,167	33,481	37,769	32,083
10	35,601	26,384	54,873	47,968	119,099	114,756	52,715	44,301	51,203	42,789
11	46,686	34,610	113,899	104,104	124,204	116,948	67,643	56,352	66,011	54,719
12	58,749	43,658	129,548	116,704	129,392	119,063	84,195	69,867	82,433	68,105
13	71,879	53,607	133,136	117,076	134,790	121,218	122,876	105,345	120,887	103,356
14	116,511	94,883	138,970	119,518	140,230	123,237	151,757	130,847	149,638	128,727
15	134,380	109,211	144,796	121,765	145,991	125,390	156,528	132,053	154,441	129,965
Total	675,561	580,255	869,756	803,416	923,679	889,440	885,807	800,576	865,246	780,012

Table 6. Annual profit and cash flow from a simulated herd expanding from 100 to 300 cows using conventional (CONV), sexed in heifers only (SS-HEIFER), sexed plus conventional (SS-CONV), sexed plus beef (SS-BEEF), or sexed plus short gestation length semen (SS-SGL) in heifers and lactating cows, assuming the conception rates achieved with sexed semen are 94% of conventional semen

	CONV		SS-HEIFER		SS-CONV		SS-BEEF		SS-SGL	
Year	Profit (€)	Cash flow (€)	Profit (€)	Cash flow (€)	Profit (€)	Cash flow (€)	Profit (€)	Cash flow (€)	Profit (€)	Cash flow (€)
1	16,863	26,923	7,445	19,584	−4,841	9,698	21,842	31,886	21,034	31,078
2	15,503	24,738	6,339	17,422	−5,400	7,815	20,910	30,131	20,044	29,265
3	18,337	26,702	1,808	11,776	−16,944	−5,126	22,924	31,276	22,008	30,360
4	22,479	29,925	11,014	19,805	−4,072	6,272	27,919	35,354	26,942	34,378
5	27,136	33,613	15,303	22,853	739	9,529	32,471	38,940	31,436	37,904
6	33,210	38,664	24,863	31,105	12,625	19,775	39,051	44,500	37,949	43,397
7	36,564	6,122	40,305	9,469	42,092	10,859	42,657	12,023	41,485	10,851
8	16,249	12,309	21,386	19,267	23,864	23,858	22,772	18,770	21,525	17,523
9	25,414	18,906	34,365	29,657	55,833	53,215	32,517	25,937	31,190	24,610
10	35,601	26,384	49,492	42,052	117,770	112,397	43,373	34,075	41,962	32,665
11	46,686	34,610	73,201	62,878	122,558	114,279	55,176	43,010	53,678	41,511
12	58,749	43,658	128,168	114,805	127,357	116,011	68,037	52,845	66,445	51,253
13	71,879	53,607	132,100	115,529	131,183	116,601	82,036	63,652	80,347	61,962
14	116,511	94,883	138,212	118,257	137,785	119,790	128,744	106,992	126,953	105,200
15	134,380	109,211	143,866	120,341	143,418	121,821	147,307	122,001	145,397	120,091
Total	675,561	580,255	827,867	754,800	883,967	836,794	787,736	691,392	768,395	672,048

Table 7. Annual profit and cash flow from a simulated herd expanding from 100 to 300 cows using conventional (CONV), sexed in heifers only (SS-HEIFER), sexed plus conventional (SS-CONV), sexed plus beef (SS-BEEF), or sexed plus short gestation length semen (SS-SGL) in heifers and lactating cows, assuming the conception rates achieved with sexed semen are 87% of conventional semen

Year	CONV		SS-HEIFER		SS-CONV		SS-BEEF		SS-SGL	
	Profit (€)	Cash flow (€)	Profit (€)	Cash flow (€)	Profit (€)	Cash flow (€)	Profit (€)	Cash flow (€)	Profit (€)	Cash flow (€)
1	16,863	26,923	10,792	22,227	1,140	14,425	26,975	35,929	26,131	35,085
2	15,503	24,738	9,646	20,103	449	12,549	25,937	34,188	25,033	33,285
3	18,337	26,702	6,049	15,474	−9,761	1,089	29,758	37,269	28,798	36,309
4	22,479	29,925	14,228	22,564	1,778	11,311	33,302	40,032	32,298	39,028
5	27,136	33,613	18,404	25,592	6,268	14,410	37,174	43,079	36,124	42,029
6	33,210	38,664	26,850	32,825	16,541	23,216	41,996	47,032	40,901	45,937
7	36,564	6,122	38,097	7,158	38,605	7,409	46,458	28,228	45,315	27,085
8	16,249	12,309	18,491	15,695	19,483	18,335	34,159	32,934	32,966	31,741
9	25,414	18,906	30,156	24,766	34,248	30,493	40,955	37,875	39,711	36,632
10	35,601	26,384	43,539	35,414	70,411	63,906	48,400	43,363	47,103	42,067
11	46,686	34,610	58,349	47,337	119,542	110,135	56,394	49,293	55,043	47,942
12	58,749	43,658	81,725	67,667	124,680	112,212	64,956	55,678	63,549	54,270
13	71,879	53,607	132,464	115,193	129,874	114,176	74,138	62,561	72,672	61,096
14	116,511	94,883	136,901	116,241	134,970	115,865	102,003	88,003	100,478	86,478
15	134,380	109,211	142,643	118,406	140,734	118,034	113,552	96,994	111,966	95,408
Total	675,561	580,255	768,334	686,662	828,962	767,565	776,157	732,458	758,088	714,392

DISCUSSION

This study used bio-economic modeling to determine the potential economic benefit of using sexed and conventional semen in heifers and lactating cows in different herd expansion strategies in a seasonal pasture-based system of dairy production. Five separate AI protocols were established and simulated under 3 scenarios of sexed semen conception rate relative to conventional semen to investigate effects on herd expansion and overall farm profit. The sexed semen AI protocols described in this study showed accelerated rates of herd expansion at 100 and 94% SS-CR compared with CONV; however, only SS-CONV and SS-HEIFER showed accelerated rates of herd expansion at 87% SS-CR. All sexed semen AI protocols demonstrated greater discounted net profit and net worth change than CONV, with the exception of SS-BEEF and SS-SGL at 87% SS-CR, both of which reported a lower net worth change due to a slower rate of herd expansion.

Conventional dairy herds generate a large surplus of male dairy calves. For example, an estimated 0.1% of all male dairy calves in the United States are selected to become dairy sires, whereas approximately 60% of breeding age heifers are required to produce an adequate number of heifers just to maintain herd sizes (De Vries et al., 2008). As the Irish national dairy herd undergoes a period of expansion, increased demand for heifers to maintain or expand herd size could result in an increase in sale prices for replacement dairy heifers (De Vries et al., 2008). This provides incentives for expanding farmers to use AI protocols such as SS-CONV and SS-HEIFER to generate surplus replacement heifers and increase discounted net profit compared with CONV. The current study also demonstrates that it may be possible to generate enough heifers in the first 3 wk of the breeding season using SS-BEEF and SS-SGL because at 100 and 94% SS-CR the rate of herd expansion was faster and similar to that of CONV, respectively, while reducing the number of male dairy calves produced. SS-BEEF and SS-SGL at 87% SS-CR had a slower rate of expansion compared with all other AI protocols used in the simulation model and did not reach maximum herd size during the 15-yr period. This lessened rate of expansion incurred a slower rate of profit increase compared with CONV, and it would require future investment to continue expanding to the target herd size of 300 cows. However, it required lower initial investment to fund farm expansion and increased discounted net profit owing to income from crossbred beef calves and longer lactations for SS-BEEF and SS-SGL, respectively. However, the net advantage from the sale of crossbred beef calves as opposed to dairy calves (Hohenboken, 1999) depends heavily on the sale price

Table 8. Discounted net profit, inventory change, and net worth change for a simulated herd expanding from 100 to 300 cows using conventional (CONV), sexed (in heifers only; SS-HEIFER), sexed plus conventional (SS-CONV), sexed plus beef (SS-BEEF), or sexed plus short gestation length semen (SS-SGL) in heifers and lactating cows, assuming 3 different sexed semen conception rates relative to conventional semen (SS-CR): 100, 94, and 87% SS-CR

SS-CR	Herd	Discounted net profit (€)	Inventory change (€)	Net worth change (€)
—	CONV	530,020	304,880	834,900
100 (%)	SS-HEIFER	663,139	304,880	968,019
	SS-CONV	693,147	304,880	998,027
	SS-BEEF	689,944	304,880	994,824
	SS-SGL	673,220	304,880	978,100
94 (%)	SS-HEIFER	633,009	306,240	939,249
	SS-CONV	665,438	306,640	972,078
	SS-BEEF	621,318	306,640	927,958
	SS-SGL	605,479	306,640	912,119
87 (%)	SS-HEIFER	590,431	307,600	898,031
	SS-CONV	626,574	308,960	935,534
	SS-BEEF	623,242	216,840	840,082
	SS-SGL	608,324	216,840	825,164

of a dairy heifer, premium attracted for a crossbred calf, and the cost of semen (McCullock et al., 2013; Ettema and Ostergaard, 2015). As all the sexed semen AI protocols demonstrated a greater discounted net profit compared with CONV, sexed semen use would allow an expanding farmer more options when choosing an expansion strategy that suits their specific business interests.

In seasonal pasture-based dairy production systems, excellent fertility is required to generate a compact calving period coinciding with the onset of spring pasture growth, enabling greater pasture utilization, longer lactations, increased milk production, and higher profitability (Dillon et al., 1995; Shalloo et al., 2004). To achieve this compact calving pattern, the majority of the herd must establish pregnancy early in the breeding season (Macmillan, 2002). In the current simulation, the calving pattern was affected by both SS-CR and AI protocol. During expansion, the proportion of the herd calving in February was similar for all sexed semen AI protocols at 100 and 94% SS-CR compared with CONV. At 87% SS-CR, the reduced fertility of sexed semen compared with conventional semen increased the proportion of cows calving in March and April, reducing the proportion of cows calving in February, and this outcome was accompanied by a reduction in discounted net profit compared with 100% SS-CR. An extended calving interval disrupts the synchrony between the supply and demand of feed, as well as a reduction in milk production (Shalloo et al., 2014). At 100 and 94% SS-CR, combining the use of sexed and conventional semen (SS-CONV) provided the greatest increase in 6-wk

Table 9. The effect of milk price variations on total profit and median annual profit for a simulated herd expanding from 100 to 300 cows using conventional (CONV), sexed (in heifers only; SS-HEIFER), sexed plus conventional (SS-CONV), sexed plus beef (SS-BEEF), or sexed plus short gestation length semen (SS-SGL) in heifers and lactating cows, assuming 3 different sexed semen conception rates relative to conventional semen (SS-CR): 100, 94, and 87% SS-CR

		€0.32/L		€0.27/L		€0.22/L	
SS-CR	Herd	Total profit	Median annual profit	Total profit	Median annual profit	Total profit	Median annual profit
—	CONV	1,480,015	79,956	675,560	33,210	−129,558	−12,105
100 (%)	SS-HEIFER	1,827,148	98,775	869,757	38,085	−88,423	−26,381
	SS-CONV	1,943,363	113,365	923,682	45,456	−96,840	−22,508
	SS-BEEF	1,770,514	95,983	885,808	39,167	373	−10,299
	SS-SGL	1,751,665	94,884	865,245	37,769	−21,904	−11,132
94 (%)	SS-HEIFER	1,762,609	94,273	827,867	34,365	−107,646	−22,938
	SS-CONV	1,880,762	105,320	883,968	42,092	−113,649	−28,321
	SS-BEEF	1,591,223	86,934	787,737	39,051	−16,411	−5,803
	SS-SGL	1,573,479	85,716	768,393	37,949	−37,357	−6,915
87 (%)	SS-HEIFER	1,670,826	89,206	768,336	30,156	−134,897	−19,900
	SS-CONV	1,794,330	96,722	828,961	34,248	−137,204	−25,998
	SS-BEEF	1,464,633	87,600	776,158	41,996	87,116	1,222
	SS-SGL	1,447,978	86,541	758,090	40,901	67,633	99

calving rate compared with CONV; however, at 87% SS-CR the greatest 6-wk calving rate was recorded in CONV because of the reduced fertility of sexed semen. It has previously been reported that farm profitability increases by €9.26/cow per year and €3.51/heifer per year for every 1 percentage unit increase in 6-wk calving rate (Shalloo et al., 2014). Despite a reduced proportion of animals calving in February in SS-CONV and SS-BEEF at 87% SS-CR because of the reduced fertility of sexed semen, CONV had the lowest discounted net profit at the end of the 15-yr period. This finding is consistent with previous research in seasonal-calving pasture-based systems (Hutchinson et al., 2013b) and may also be applicable to confinement feeding systems that use block calving. In addition to the increased farm profitability and number of heifers generated through sexed semen usage, concentrating the calving period would reduce involuntary culling rates and breeding costs and increase genetic gain (Plaizier et al., 1997), thus increasing the rate of expansion and discounted net profit of the business.

Heifer fertility was a key driver of herd expansion because AI protocols that generated more replacement heifers quicker had an increased rate of expansion compared with CONV and SS-BEEF and SS-SGL at 87% SS-CR. Embryo mortality in heifers following AI was not included in this model because previous research has reported that the incidence of embryo mortality is very modest in heifers compared with lactating dairy cows owing to increased embryo quality (Diskin et al., 2011), reducing potential effects on calving rate. To overcome any negative effects of embryo mortality in heifers or potentially increase heifer fertility performance, a synchronization protocol could be used to advance heat onset and increase the number of heifers that become pregnant at the start of the breeding period. Based on the results observed in the current study, the use of synchronization or additional heat detection measures may be most important for SS-BEEF and SS-SGL, in which all dairy inseminations were restricted to the first 3 wk of the breeding season. This approach could be particularly useful at 87% SS-CR because the rate of herd expansion was reduced compared with CONV. Any potential increases in heifer fertility and SS-CR could facilitate increases in both expansion rate and discounted net profit for the farm business.

This study shows that sexed semen use could be profitable under most conditions, and it supports the findings of McCullock et al. (2013), in which sexed semen was deemed to be generally profitable when other measured variables were favorable (e.g., milk price, feed price, calf prices, semen costs, and conception rate). Over the full 15-yr simulation, SS-CONV was the most profitable AI protocol under each assumption of SS-CR because of faster expansion. The increased rate of expansion for SS-CONV required greater investment in yr 1 to establish facilities and housing to accommodate additional livestock. However, these facilities were not fully occupied until yr 7 of the simulation and had an effect on depreciation costs, resulting in significant negative cash flow during the initial period of expansion. Milk price plays a key role in the severity of financial risk in SS-CONV during the expansion period. A high milk price eliminated these negative cash flows and doubled the total profit of the farm business at all SS-CR. Additionally, SS-CONV and SS-HEIFER

Table 10. Effect of variations in the sale price of calves sold for beef (male dairy and all crossbred beef calves) on total profit and median annual profit for a simulated herd expanding from 100 to 300 cows using conventional (CONV), sexed (in heifers only; SS-HEIFER), sexed plus conventional (SS-CONV), sexed plus beef (SS-BEEF), or sexed plus short gestation length semen (SS-SGL) in heifers and lactating cows, assuming 3 different sexed semen conception rates relative to conventional semen (SS-CR): 100, 94, and 87% SS-CR

		Beef sale price + €30		Beef sale price ± €0		Beef sale price − €30	
SS-CR	Herd	Total profit	Median annual profit	Total profit	Median annual profit	Total profit	Median annual profit
—	CONV	722,901	35,802	675,560	33,210	628,219	30,618
100 (%)	SS-HEIFER	912,737	41,302	869,757	38,085	826,777	34,869
	SS-CONV	957,560	47,696	923,682	45,456	889,803	43,216
	SS-BEEF	914,678	41,169	885,808	39,167	856,938	37,166
	SS-SGL	894,115	39,770	865,245	37,769	836,376	35,768
94 (%)	SS-HEIFER	870,348	37,445	827,867	34,365	785,385	31,285
	SS-CONV	918,199	44,269	883,968	42,092	849,736	39,914
	SS-BEEF	814,888	40,528	787,737	39,051	760,586	37,574
	SS-SGL	795,544	39,426	768,393	37,949	741,242	36,472
87 (%)	SS-HEIFER	809,957	33,080	768,336	30,156	726,716	27,232
	SS-CONV	863,408	36,954	828,961	34,248	794,514	31,542
	SS-BEEF	800,659	43,423	776,158	41,966	751,657	40,570
	SS-SGL	782,590	42,328	758,090	40,901	733,589	39,475

demonstrated the greatest profits gains regardless of SS-CR when milk price was high. Alternatively, during periods of reduced milk price, total farm profit was negative in both SS-CONV and SS-HEIFER for each SS-CR. SS-BEEF and SS-SGL at 87% SS-CR provided the only AI protocols that made a substantial profit in periods of low milk price. This outcome was due to slower herd expansion and reduced operating costs. Although SS-CONV may be the best expansion option for profitability over the 15-yr period of growth, this result is heavily dependent on favorable milk price, and the business may become unviable if significant funding is not available to survive prolonged periods of negative cash flow.

CONCLUSIONS

The current study examined a variety of strategies for sexed semen use when expanding from 100 to 300 lactating cows in a hypothetical seasonal-calving pasture-based dairy herd subjected to 5 separate AI protocols under 3 SS-CR scenarios. Using sexed semen generally facilitated faster herd expansion and increased discounted net profit compared with CONV. The quickest expansion strategy, SS-CONV, resulted in negative cash flows with high-fertility sexed semen (100 and 94% SS-CR) during the period of most rapid expansion and at all SS-CR when milk price was low, placing the viability of the farm business at risk. Combining sexed semen use with conventional beef or SGL semen provides expanding farmers with alternative strategies that have the potential to generate additional income. Reports of advancements in sorting technology and the fertility of the frozen semen product are promising; however, further work is required to validate the findings from this simulation model before widespread adoption of sexed semen at the farm level occurs.

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