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Agent-Based Modeling to Improve Beef Production from Dairy Cattle: Model Description and Evaluation

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Abstract: Agent-based modeling (ABM) enables an in silico representation of complex systems and captures agent behavior resulting from interaction with other agents and their environment. This study developed an ABM to represent a pasture-based beef cattle finishing systems in New Zealand (NZ) using attributes of the rearer, finisher, and processor, as well as specific attributes of dairy-origin beef cattle. The model was parameterized using values representing 1% of NZ dairy-origin cattle, and 10% of rearers and finishers in NZ. The cattle agent consisted of 32% Holstein-Friesian, 50% Holstein-Friesian–Jersey crossbred, and 8% Jersey, with the remainder being other breeds. Rearers and finishers repetitively and simultaneously interacted to determine the type and number of cattle populating the finishing system. Rearers brought in four-day-old spring-born calves and reared them until 60 calves (representing a full truck load) on average had a live weight of 100 kg before selling them on to finishers. Finishers mainly attained weaners from rearers, or directly from dairy farmers when weaner demand was higher than the supply from rearers. Fast-growing cattle were sent for slaughter before the second winter, and the remainder were sent before their third winter. The model finished a higher number of bulls than heifers and steers, although it was 4% lower than the industry reported value. Holstein-Friesian and Holstein-Friesian–Jersey-crossbred cattle dominated the dairy-origin beef finishing system. Jersey cattle account for less than 5% of total processed beef cattle. Further studies to include retailer and consumer perspectives and other decision alternatives for finishing farms would improve the applicability of the model for decision-making processes.

Keywords: agent-based modeling; dairy cattle; beef finishing; rearer; finisher

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1. Introduction

In New Zealand (NZ), a significant proportion of dairy-origin cattle are artificially reared and grown for beef [1–4]. The number and types of dairy-origin calves that are ultimately processed for beef production requires successful co-operation among the dairy farmer, rearer, finisher, processer, and consumer [2,5,6]. The interaction among and between these sectors creates a phenomenon that cannot be simply explained by any single agent [7–10], nor can the collective behavior from these complex interacting sectors be captured by static mechanisms of modeling [7].

Modeling systems such as agent-based modeling (ABM) can capture the behavior of all agents and their subsequent behavior that is derived from their interaction [8–10]. Agent-based modeling uses computing algorithms to simulate how agents behave depending on the behavior of other agents and their environment [8–11]. In ABM, agents are autonomous, but are capable of adapting to and anticipating behaviors that emerge during interactions [9]. Agent-based modeling allows for repetitive and competitive interactions between agents, which enables the exploration of dynamics over time [9,12–14].

To date, few studies have been conducted to understand the application of in silico ABM representation of socioeconomic and ecological impacts within livestock production systems [15,16]. Agent-based modeling has been employed to understand beef cattle production and transportation issues in Southwest Kansas, USA [17], to compare beef reproductive strategies in Brazil [18], and to represent meat consumption behavior in the United Kingdom [19].

The current study developed an ABM to represent the NZ dairy–beef production chain using rearer, finisher, and processor as agents, and accounting for specifics of individual animals, such as their breed and sex. It includes stochastic elements that can account for random variables such as date of birth, birth weight, and growth rate, and per head calf prices and variable attributes of the rearer, finisher, and processor. The study defined the availability of dairy-origin beef cattle in NZ, accounting for the expected proportions of heifer, steer, and bull calves. The simulation was parameterized based on calves born in 2018 from the dairy industry [20]. Among these, some of the fastest-growing cattle were finished and slaughtered in 2019, and the remainder were slaughtered in 2020 [21,22]. The total number of slaughtered dairy-origin heifers, steers, and bulls was compared with animal values reported by Beef and Lamb New Zealand [23].

2. Material and Methods

2.1. The Julia Programming Language

The attributes of rearer, finisher, and processor, and specific attributes of dairy-origin beef cattle were represented using the Julia framework for agent-based modeling (Agents.jl) [24]. Julia is a dynamic programming language designed to address the requirements of high-performance numerical and scientific computing [25]. A simplified representation of dairy-origin beef cattle finishing on sheep and beef cattle farms including a dynamic supply of various breeds of cattle respectively owned by a rearer, finisher, and then processor as agents is presented in Supplementary Figure S1.

2.2. Description of Agents and Model Parameterization

2.2.1. Cattle

The model was parameterized with 45,000 spring-born (July to September) dairy-origin calves [3,25,26] at 1:1 female to male ratio [2]. This represented 1% of the NZ dairy-origin calf population. Dam breed proportions consisted of Holstein-Friesian (32%), Holstein-Friesian–Jersey cross (50%), Jersey (8%), and other (10%) [3,26–28] representing breed proportions of herd-tested first calving dairy heifers in New Zealand over the last five years. Dairy-origin calves that are greater than 14/16 Holstein-Friesian are defined as Holstein-Friesian, and calves that are greater than 14/16 Jersey are defined as Jersey calves [3,25,27]. The "other" category was assigned the same properties as the Jersey breed, due to insufficient information, but could be modified in the future if new information becomes available. In each breed, 80% of the calves produced to these dams were from a dairy breed, and the remaining 20% were a beef–dairy crossbreed (mainly Angus and Hereford) [29]. Within each dairy breed, 25% of the total female calves were excluded from the beef supply chain as they became dairy herd replacements [2]. For male calves, 50% were processed as steers and the remainder as bulls, except for the Holstein-Friesian breed, where all male calves were finished as bull beef, per current NZ industry data [6,30,31].

The distribution of date of birth was based on the within-herd calving distribution from herd-tested dairy farms throughout NZ in 2019. A linearly transformed Poisson distribution function [32] was used to provide a location parameter that, along with the within-herd calving distribution location, reconstructed the national distribution of date of birth over the three-month Spring calving period. Average birth weight, slaughter weight, age at slaughter, and prices per calf and per kg carcass for dairy-origin beef cattle were parameterized using data collected from various studies (Table 1). Birth weight and per head calf price were distributed with ± 2 kg and $\pm$ NZD 5 standard deviations [3,33], respectively. A multivariate normal distribution function was employed to simulate positively correlated birth weight, growth rate, and price of calf [34]. Average birth weights for bull and steer calves were the same; however, bulls grew faster than steers (Table 1; Supplementary Figure S3). A four-parameter Richards growth equation [35] was employed to model the growth curves of the various beef cattle breeds (Supplementary Figure S2) [27,31,36].

Table 1. Birth weight, minimum weight at slaughter, slaughter age, per head calves, and per kg live weight weaners prices of various classes of dairy-origin beef cattle.

Attributes	Holstein-Friesian			Holstein-Friesian–Jersey			[a] Jersey			References
	Heifer	Steer	Bull	Heifer	Steer	Bull	Heifer	Steer	Bull	
* Birth weight, kg	36.1	38.2	38.2	31.7	33.9	33.9	27.6	29.8	29.8	[3]
Minimum weight at slaughter (kg)	500	-	550	500	580	550	500	580	550	[1,37–42]
Adjusted average age at slaughter (d)	610	-	600	679 +	896	805	700 +	920	880 +	[37–39,43]
Calf price/head (NZD)	90	-	110	80	100	100	70	90	90	[33,44]
Weaner price/kg live weight (NZD)	3.70	-	4.50	3.60	3.70	4.00	3.00	3.20	3.20	[33,44]
	Beef–Holstein-Friesian cross			Beef-Holstein-Friesian–Jersey cross			Beef–Jersey cross			
* Birth weight, kg	38.3	40.2	40.2	37 +	39 +	39 +	35 +	37 +	37 +	[34,40]
Minimum weight at slaughter	500	580	550	500	580	550	500	580	550	[1,37–42]
Adjusted average age at slaughter (d)	561	663	625	579 +	689	640	600 +	750 +	703 +	[6,37]
Calf price/head	95	120	120	90	110	110	75	95	95	[33,44]
Weaner price/kg live weight	3.90	4.00	4.70	3.60	3.70	4.00	3.00	3.20	3.20	[33,44]

* Male calves' birth weight was 2.2 kg heavier [3]; + estimated based on the value of other classes and breeds; [a] includes "other breed" category; heifers, steers and bulls carcass weights were estimated as 50, 54, and 52 % of live weight, respectively [41,42,45].

2.2.2. Rearers

Calf rearing requires a limited land area with housing facilities for the purpose of rearing calves to weaning [31]. In some cases, rearers are the calf producers (i.e., dairy farmers) or beef cattle finishers. However, the majority of rearers purchase spring-born (July to September) calves at four days old and then sell these calves to finishers at an average weaning weight of 100 kg [5,6,30]. The current study assumed the number of rearers to be 10% of the number of dairy farmers (i.e., 10% of 11,890). This reduces computational effort compared to a greater number of rearers, but does not compromise the heterogeneity of rearers [45]. Rearing capability followed one of three Poisson distributions, with 10% of rearers having mean capacity of 100 calves, 80% of rearers having mean capacity of 500 calves, and 10% of rearers having mean capacity of 1000 calves [31,45]. If the rearers' weaning capability was greater than the number needed by finishers, they subsequently adjusted the numbers reared to secure a market to sell weaners (Supplementary Figure S1). In contrast, when there was high weaner demand from the finishers, rearers bought calves up to their maximum rearing capacity to on-sell to finishers.

In the current study, rearers had no geographic limitations during calf procurement, indicating that they could access all available calves and evaluate their attributes to predict weaning period and weight, production and transport costs, and returns at weaning. When rearers and calves had interacted, rearers started price negotiation by offering a 10 $\pm$2% lower purchasing price (normally distributed) from the given selling price of a calf. This behavior should be attributed to dairy farmers; however, to reduce the complexity of the agents and computation time, the cattle agent had this attribute on behalf of their dairy farm owners. The sellers reduced their selling price and rearers increased their purchasing price by 0.1% of their previous amount until they reached an equilibrium point. The calf price did not reduce if the number of calves available for sale was lower than the demand. During price negotiation, if the calf price dropped lower than the bobby calf price (price supplied by meat processors for processing calves at approximately 7 days old), the calves were processed as bobby calves rather than being reared, along with other calves that were light and slow growing [20,46,47].

Once the price equilibrium point was achieved, rearers predicted the per head production cost, revenue, and margin of calves for a 100-day weaning age [6,31,48]. Calves with a higher margin, which were potentially fast-growing, heavier calves, and those from locations closer to rearers, were selected and transported to a rearing facility [3,47,49]. The calf transportation cost was estimated as the distance of a calf from the rearer times NZD 2 per km [31]. Calves were weaned and sold when the average weight of 60 calves (assumed to be a full truck carrying capacity) attained 100 kg live weight. Then, actual production cost, revenue, and margin of weaners at sale weights were calculated, which could be different from the predicted value, as some calves grow faster or slower to achieve the target weaning weight. The calf rearing cost to 3 months [31], including labor and feed, was evenly distributed per day to estimate a rearing cost at weaning. Calf revenue was calculated as a function of live weight and price per kg live weight at weaning (Table 1) [33]. A calf margin was estimated as the difference between the costs for calf purchase, production and transport, and the revenue from the sale of the calf [22].

2.2.3. Finishers

To reduce computational effort, only 10% of 9165 finishers were included in the ABM [45]. They were split into small, medium, and large holder finishers at a 20:60:20 ratio [5] and had one of the three Poisson distributed farm areas with means of 100, 500, or 1000 hectares [22], respectively. Monthly average pasture growth rate, utilization percent, and megajoules metabolizable energy per kilogram dry matter were taken from the literature [21,50]. The total average pasture mass was the sum of the previous day and the net pasture growth in a period, except that it had to remain between 1500 kg DM and 2500 kg DM minimum and maximum pasture covers [51–53]. This was multiplied by utilization percent (i.e., 70 to 90%) to estimate the available utilizable kg DM for cattle activities. Detailed descriptions of feed supply and pasture cover calculation can be found in [54]. Of that, 20% was allocated to the dairy-origin cattle and the remaining to beef cattle and sheep bred on the sheep and beef cattle farm, which was used to determine the total carrying capability of a finisher.

Finishers mainly purchased weaners from rearers, with the remainder from dairy farms when the weaner demand was higher than the supply from rearers [47]. The finishers sold them when 30 cattle per finisher (i.e., a full truck carrying capacity) attained targeted slaughter weight. Heifers, bulls, and steers were finished from 480, 500, and 550 kg live weight, respectively [37,39,55], when the total feed demand of cattle was greater than the consumable feed supply [54,56]. However, slaughtering weights were extended to a minimum of 500, 550, and 580 kg respectively when there was sufficient consumable feed supply. At these slaughter weights, fast-growing cattle were finished before their second winter (R2-cattle) and the remainder before their third winter (R3-cattle) [54,56]. Carcass weight was assumed to be 50, 52, or 54% of final slaughter weight for heifers, bulls, or steers, respectively [41,42,57].

2.2.4. Processors

There are 60 commercial meat processing plants, excluding home-kill butchers, throughout New Zealand [58]. These plants primarily slaughter animals (excluding poultry), bone-out carcasses, and freeze or chill meat products [59]. New Zealand processed approximately 331,000 heifers, 161,000 steers, and 520,000 bulls with dairy origins in 2019. In 2020, these corresponding numbers were 228,000, 159,000, and 511,000 [23]. Beef heifers and steers were given the historical average price of NZD 5.50 per kg carcass weight, or NZD 5.25 for bull beef [22].

2.3. Evaluation of Model Outputs

To quantify the uncertainty and robustness of the model and determine minimum simulation runs, variance stability, which can be expressed as coefficient of variation (CV), was analyzed across a set of 10, 20, 30, and 40 simulation runs [60,61]. The minimum number of ABM simulation runs was fixed when the absolute difference of two consecutive sample set CVs became lower than the fixed value (i.e., 0.005 confidence interval) [60,61] (Supplementary Table S1). Further, a total of 100,000 bootstrap replicates using Bootstrap.jl [62] were carried out to estimate mean and variance of each class of dairy-origin beef cattle. These figures were then compared to mean and variance of ABM simulation at 95% confidence level (Supplementary Table S2). The slaughtered numbers of dairy-origin heifers, steers, and bulls from this study were also compared to the actual numbers of heifers, steers, and bulls finished in 2019 and 2020 as part of the model validation to make sure that the results were sensible in the context of the New Zealand beef production industry [23].

3. Results

One hundred ABM simulation runs were performed, representing 1% of New Zealand's total number of dairy-origin calves and 10% of the rearers and finishers. The profit motive of the agents in the ABM resulted in a slight discrepancy in the sex ratio of finished cattle compared to the industry statistics (Table 2). The number of steers processed in this study was 8% higher than the value reported by B + LNZ in 2020 (Table 2). In contrast, the current study processed 8% less heifers and 4% less bulls of dairy origin compared to the values reported by B+LNZ in 2020 (Table 2). However, the industry means were within the ABM means ± one standard deviation. On average, heifers accounted for 28%, steer 19%, and bulls 53% of the total number of processed dairy-origin beef cattle (Table 2).

Table 2. Mean and standard deviation (sd), final slaughter weight of traditional dairy-origin beef cattle in the ABM and actual reported B+LNZ * numbers (the number represented 1% of dairy-origin beef cattle processed in New Zealand based on the average of 2019 and 2020 processing statistics).

Class of Beef Cattle	B + LNZ Industry Data		Mean ± sd of the 100 Runs of ABM	
	[a] Number, n	[b] Slaughter Weight, kg	Number, n	[c] Slaughter Weight, kg
Heifer	2800	484	2562 ± 186	480/500
Steer	1600	579	1744 ± 151	550/580
Bull	5160	576	4952 ± 282	500/550
Total	9560	-	9257	-

[a] 1% of dairy-origin beef cattle processed in New Zealand, [b] estimated from carcass weight reported by [21,58] using 0.5%, 0.54%, and 0.52% dressing-out percentage for heifer, steer, and bull beef, respectively; [c] two minimum slaughter weights were allocated for fast-growing or slow-growing beef cattle for each beef cattle class; * Beef and Lamb New Zealand.

Figure 1 shows that the total number of bulls remained lower than the average reported value (red lines) across 100 runs of ABM. However, the numbers of steers and heifers were above the mean until approximately the 10th run (black and blue lines) before reducing for heifers (Figure 1).

Figure 2 summarizes the number of dairy-origin cattle (i.e., sum of beef–dairy and dairy–dairy calves) within respective dam breed type that were finished for beef production in the ABM model simulations. Holstein-Friesian and Holstein-Friesian–Jersey-cross bulls accounted for approximately 49% of the total finished beef cattle. The Jersey breed contributed less than 5% of total dairy-origin beef breed cattle processed in ABM study.

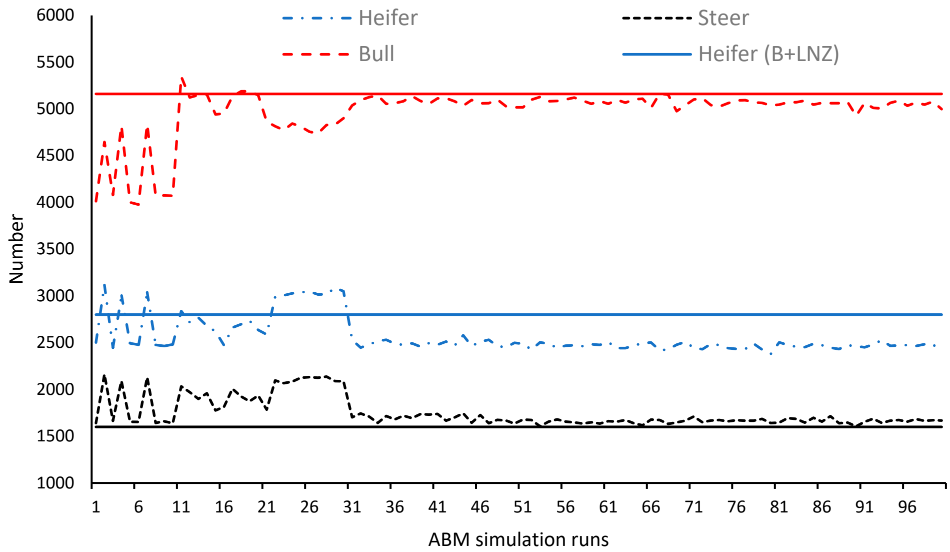

Figure 1. The total number of traditional dairy-origin heifer (blue dash dotted line), steer (black dotted line), and bull (red dashed line) processed in the ABM across each of the 100 runs. The solid lines in each class of beef cattle represented the actual Beef and Lamb New Zealand (B + LNZ) average values.

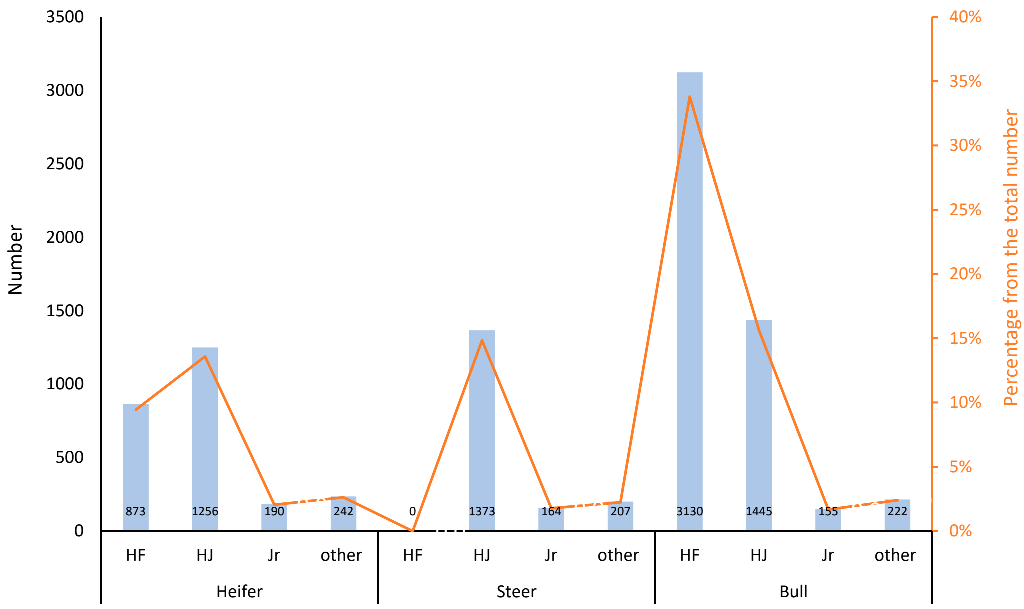

Figure 2. The average number of traditional finished heifer, steer, and bull across dam breed types in the ABM (left axis, blue bars) and percentage from the total number (right axis, orange line); HF: Holstein-Friesian; HJ: Holstein-Friesian–Jersey cross, Jr: Jersey and other cattle.

4. Discussion

Agent-based modeling (ABM) can be utilized in silico to represent complex systems [8,17,19]. It has been employed to represent beef cattle production and transportation issues in southwest Kansas, USA [17], to compare beef reproductive strategies in Brazil [18], and to represent meat consumption behavior in the United Kingdom [19]. This study developed an ABM to represent the succession of dairy-origin beef cattle in New Zealand from birth to slaughter using the attributes of rearers, finishers, and processor agents, and the specific attributes of dairy-origin beef cattle. This enabled agents to interact and select cattle with potentially higher returns for finishing [9,12,14].

Bulls grow 10–20% faster than other sex classes of cattle [63,64]. This increases their demand for bull-beef finishing, as they are likely to be more profitable on a per kg of dry matter eaten basis [5,30]. The ABM showed that bull-beef cattle accounted for more than 50% of the total dairy-origin beef cattle processed. The number of bulls from the industry report falls within one standard deviation of the current study, being 4% higher [23]. The variation, while small, might be explained by bull-beef receiving a lower per kg carcass price compared to steers and heifers [21].

Holstein-Friesian and Holstein-Friesian–Jersey cross-bred cattle are preferred for dairy-origin bull finishing systems, as they grow faster and likely attain the targeted slaughter weight earlier than Jersey types [30,31]. Therefore, their dominance in the industry data and the ABM was not unexpected. In contrast, Jersey breed-type cattle accounted for less than 5% of the total dairy-origin finished beef cattle in the model. This is likely explained by their lighter live weight and slower growth rate compared to other breeds [6,25,30,31]. This suggests that the New Zealand dairy industry needs a breeding strategy to improve growth rates and thus increase the acceptance of these cattle for beef finishing [34,39,40], or to find alternative uses which are less driven by live weight and growth rate, such as Asian markets, where lighter carcasses are the norm.

In New Zealand, Jersey bulls could be preferred to sire first-calving 2-year-old heifers in the dairy industry to reduce calving difficulty [34,40]. However, calves from these matings are typically not used for dairy herd replacements, nor preferred for beef finishing on sheep and beef farms, as they grow more slowly and do not achieve heavy carcasses [3,30,63,64]. Another option instead of Jersey bulls is using selected beef sires from other breeds that have the potential to improve the growth rate of beef–dairy cattle for beef finishing [39,40]. Coleman et al. 2022 [40] identified that Angus and Hereford bulls with low birthweight and high calving ease estimated breeding values can be used to produce calves of greater value than Jersey-sired calves. Using these beef breed bulls to improve the value of non-replacement Jersey calves from Jersey cows and first calving heifers would increase the value of Jersey type calves and their acceptance for a beef finishing system on sheep and beef cattle farms [39,40].

A four-parameter equation [35] was employed to simulate the growth curves of the various breeds in this study. Live weight change was based solely on the growth stage of the animal and did not consider the variability in feed supply across seasons. In New Zealand, pasture-based outdoor grazing is the predominant beef production system [65]. It is important to acknowledge this limitation of the growth simulation equation in this study, as body growth at some stages may be limited by feed supply, thereby reducing the growth rates simulated in the ABM. Likewise, the effects of compensatory growth when feed supply is abundant were not incorporated. It would be possible to modify the modeled growth to account for the feed supply [27]. This would allow farmers to sell their cattle when they do not have sufficient feed during winter, when others might be in a situation to carry over cattle through to the third winter by allowing either no change in live weight or weight loss during the winter period, which could be regained through compensatory growth in spring [66,67].

5. Conclusions

Agent-based modeling was used to represent pasture-based beef production systems in New Zealand and allowed rearers and finishers to interact among themselves in determining breed and class type for dairy-origin beef cattle finishing. The model finished a higher number of bulls than heifers and steers. Holstein-Friesian and Holstein-Friesian–Jersey-crossbred cattle dominated the dairy-origin beef production system. Further studies to include retailer and consumer perspectives, as well as other decision alternatives for finishing farms, would improve the applicability of the model to support decision-making processes.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agriculture12101615/s1, Figure S1: Agent interactions that determine the number and type of dairy-origin cattle entering the beef production chain (agents are represented by the rectangular boxes, the diamond boxes are decisions made by agents, the oval boxes are the final decisions to be executed); Figure S2. Growth curve of dairy-originated cattle in New Zealand simulated using the Richards four parameter equation. The left side of the graph represented for beef-dairy cattle and the right side dairy-dairy cattle. In both columns, heifers, steers and bulls from top to bottom (black solid line stood Holstein-Frisian origin, dotted red line for Jersey origin and the blue dashed line for their crosses; Figure S3. Distribution of slaughtering age across breed and class in the ABM. The orange, green and blue scatters represent dairy-origin heifer, steer and bull beef cattle respectively. HF: Holstein-Friesian; HJ: Holstein-Friesian–Jersey cross, Jr: Jersey; Ot: Other cattle; prefix B_ in represents beef-dairy cross in each breed; Table S1. Variance stability analysis; Table S2. Bootstrap analysis at 95% confidence interval.

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