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PRODUCTION AND MANAGEMENT: *Original Research*

Can early weaning calves of first-calf heifers improve long-term herd and financial performance in a vertically integrated beef production system? A study application using system dynamics

Jase K. Taylor,[1] Randy L. Stanko,[2,3] Ryan Rhoades,[4] Kimberly C. McCuistion,[5,6] Clay Mathis,[6] PAS, Richard Machen,[6] and Benjamin L. Turner[6,7]*

[1]Ranch Management, Texas A&M University–Kingsville, Kingsville 78363; [2]Department of Animal Science and Veterinary Technology, Texas A&M University–Kingsville, Kingsville 78363; [3]Animal Reproduction Laboratory, Texas A&M Agrilife Research, Beeville 78102; [4]Department of Animal Science, Colorado State University, Fort Collins 80523; [5]Tarleton State University–Fort Worth, Fort Worth, TX 76036; [6]King Ranch Institute for Ranch Management, Texas A&M University–Kingsville, Kingsville 78363; [7]Department of Agriculture, Agribusiness, and Environmental Science, Texas A&M University–Kingsville, Kingsville 78363

ABSTRACT

Objectives: The objectives were to (a) evaluate whether marginal reproductive gains from early weaning (EW) calves of first-calf replacement heifers extend throughout the animal's productive life and (b) compare via cost–benefit analysis EW with conventional weaning (CW) practices on a vertically integrated ranch in Florida, USA.

Materials and Methods: A system dynamics model was developed to evaluate CW versus EW of calves from replacement heifers that calve in the first 21 or 42 d of the calving season. A combination of sensitivity analyses and deterministic management tests (EW vs. CW and 21- vs. 42-d calving seasons) were simulated and compared across a range of 18 production and financial metrics, including net present value, over the useful life of one generation of replacement heifers. We hypothesized that EW calves from replacement heifers would improve reproductive performance, resulting in greater total calves produced and, therefore, improved cow-calf and whole-system profitability.

Results and Discussion: The 42-d calving criteria for EW created significant production and financial gains and outperformed the 21-d calving criteria. Counterintuitively, these gains did not arise in the cow-calf or feedyard segments (which saw financial declines) but in the stocker segment due to more efficient livestock gains facilitated by lower weaning weights of incoming calves. Sensitivity analyses corroborated these trade-offs. Feedyard sale price (i.e., value received for finished cattle) was the most influential factor influencing whole-system profitability.

Implications and Applications: Trade-offs and incentives between enterprises may provide misleading feedback and mask changes that improve the system as a whole (e.g., EW reduced calf weaning weights and reinforced the reproductive performance pressure on management; gains at the stocker segment may mask EW benefits at the cow-calf level, making the cow-calf enterprise more reliant on short-term adjustments, a behavior known as "shifting the burden").

Key words: heifer management, ranching systems, simulation modeling, vertical integration, weaning decisions

INTRODUCTION

Rebreeding primiparous replacement heifers can have up to twice the rate of reproduction failure compared with dams 4 yr old or older (Roberts et al., 2015). Both the length of postpartum anestrus and postpartum interval (**PPI**) are known factors influencing conception (Bischoff et al., 2015). Length of postpartum anestrus is driven by heifer BCS (Arthington and Vendramini, 2013), which subsequently drives pregnancy rate (Wiltbank et al., 1961). Cow BCS before and after calving can be one full BCS lower, with replacement heifers typically having the lowest BCS after calving (Odhiambo et al., 2009). Successful conception requires replacement heifers reach BCS 6 at calving (Payne et al., 2013); BCS below 5 may yield pregnancy rate reductions as high as 25% (Kunkle et al., 1998). Additionally, to maintain a 365-d calving interval, cows must maintain a PPI of less than 82 d (283-d gestation + 82-d PPI = 365 d; Cushman et al., 2013). If replacement heifers

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*Corresponding author: benjamin.turner@tamuk.edu

cannot achieve this, they must be placed on a higher nutritional plane (i.e., allowance for NE_g; Galindo-Gonzalez et al., 2007; Hersom 2013; Johnson and Funston, 2013). Short-term strategies (e.g., supplementation to maintain BCS) may mask indicators of longer-term reproductive issues while adding significant costs.

Early weaning (**EW**) calves from primiparous replacement heifers could improve reproductive success given the feedback relationships that influence NE requirements, BCS, and PPI, which collectively drive pregnancy rate (Lusby et al., 1981; Peterson et al., 1987; Rasby, 2011, Martins et al., 2012; Bischoff et al., 2015; Arthington, 2016). If EW occurs before the bull exposure, reproductive success is significantly enhanced (Arthington and Kalmbacher, 2003, Arthington and Minton, 2004; Arthington and Vendramini, 2013; Perry and Cushman 2013), while simultaneously improving economic returns (Myers et al., 1999a,b,c; Thrift and Thrift, 2004; Galindo-Gonzalez et al., 2007; Odhiambo et al., 2009). This is usually 80 to 90 d after calving, necessitating that the earliest calves be weaned at 50 d of age; however, it has been difficult for many ranches to wean before 70 d (Arthington and Vendramini, 2013).

The objectives of this project were to examine the following research questions to determine the potential reproductive gains attributable to EW for a large-scale, vertically integrated Brahman-crossbred (hybrid *Bos indicus/taurus*) beef production operation headquartered in Florida, USA:

1. Will the marginal reproductive gains from early weaning calves of first-calf replacement heifers (measured as the change in calf production over the life of the replacement heifers) extend throughout the female's productive life?
2. If EW calves from replacement heifers is a feasible biophysical strategy, do the benefits of altering the cow-calf production practices outweigh the costs to the entire integrated system compared with the current conventional weaning (**CW**) practice?

MATERIALS AND METHODS

Model Conceptualization

A system dynamics model was constructed to capture key feedbacks influencing reproductive performance in the beef cattle operation, namely BCS, PPI, and pregnancy rate interrelationships, to analyze several scenarios capable of addressing the objectives described previously (additional description of the system dynamics method is provided in the Supplemental Material, https://doi.org/10.15232/aas.2021-02235). After initial review of ranch-level data, data in the literature, and discussions with management on the ground, we developed a dynamic hypothesis (i.e., a working theory regarding the core feedback processes of the problem and its behaviors over time; Turner et al., 2016a; Turner 2020), stated as follows:

> "Ranchers in Florida find it difficult to rebreed primiparous Brahman crossbred heifers on time because they often reach puberty later than desired and are required to graze poor forage quality. Those females that do become pregnant often conceive late in the breeding season, resulting in younger, lighter calves at weaning. Additionally, these animals have a greater tendency to fail to conceive during the desired breeding season and therefore fail to meet management's goal of a 365-day calving interval. Having a large percentage of open females necessitates culling of replacement heifers, and inflates cow costs because of the concomitant increase in heifer development expense. To hedge against the resulting elevated culling rates and to meet high nutrient demands, BCS required to rebreed is achieved by grazing annual Ryegrass (*Festuca perennis*; about 2 hectares or 5 acres planted per head) and heavy supplementation. With large variability in annual Ryegrass forage production, costly supplementation is often heavily relied upon. As the number of females falling out of the system rises and costs escalate, management pressure to ensure primiparous heifers rebreed increases." (Figure 1)

The hypothesis captures the model core structure, providing the baseline, status quo conditions (similar to a null hypothesis) that our EW hypothesis tests aimed to refute, and by doing so, provide evidence for EW as a potential leverage point for beef system improvement.

Quantitative Model Development

The model was designed to follow one generation of cows, beginning with their first calves as replacement heifers, to the depletion of the generation out of the herd. By encompassing all stages of the production cycle, we estimated this cow generation's total calf production from the cow/calf enterprise through the stocker and finally feedyard segments. Costs of production through each segment were accumulated annually. Because the business system is vertically integrated, calf revenue was not generated until finished cattle were sold from the feedyard. The model was compartmentalized by production segment beginning with the initial generation of replacement heifers. Calves move through each enterprise beginning at cow-calf until they are sold as fat cattle. Cost generation was matched with each production segment.

The mathematical model was constructed in the Vensim modeling environment (Ventana Corp.) using stocks, flows, and auxiliary variables. The unit of time used for simulation was 1 d with a time horizon of 15 yr (the estimated time to see one generation of cows completely culled from the herd). A time unit of 1 d was chosen due to the nature of the production system (i.e., activities are sensitive to the day of the year such as weaning date, breeding season day and weight, number of days stockers are grazed, and so on; DeRouen and Franke, 1989). An overview of the stocks, flows, and variables used to model the production system are given in Supplemental Table S1 (https://doi.org/10.15232/aas.2021-02235), and mathematical equations for core variables are detailed in the following sections (italicized words throughout the remainder of the text correspond with variable names). Historical data provided by management were used as a framework to construct and calibrate the model and provided assumptions for the EW and CW scenarios. Each compartment of the model is described in the following.

Cow Production Line. The cow production line was formulated by cattle age, in which cattle progress through the system according to death loss and pregnancy status (Table 1; Figure 2). Primiparous cattle (initial value of 5,000 head to approximate actual scale of the operation) were exposed to bulls on February 15, 95 d after the first-calf heifer due date. The production line then starts with *yearling conceived in allotted time*, which was the basis for the number of animals conceiving early enough in the breeding season to allow calves to be old enough for EW. In the current production system, only the first-calf heifers that calve in the first 21 d of calving season are old enough for EW. Calves born after the first 21 d of the calving season would not meet the 70 d of age recommended for EW before cow exposure to bulls. Therefore, only those females with calves born in the first 21 d are *2-yr-olds eligible for EW* and could later be compared with CW.

The *yearlings conceived in the allotted time* begin in the system as *2-yr-olds eligible for EW*. Depending on whether cattle are EW or CW dictates the *2-yr-old EW/CW pregnancy rate*, as well as the number of cattle that will be maintained in the cow herd as *open 3-yr-olds* (open heifers at 2 and 3 yr of age are kept for one additional year; all heifers are culled when identified as open a second time; Figure 2). Because *BCS at calving* will influence the PPI and pregnancy rate; the change in BCS due to EW affects the *3-yr-olds pregnancy rate* and PPI through the *BCS and pregnancy rate interaction* (a table function that specifies increasing pregnancy rate with increasing *BCS at calving* up to a score of 6). Cattle diagnosed as pregnant as *3-yr-olds* or *open 3-yr-olds* flow into the *>3-yr-old* stock (Figure 2). Cattle from 4 to 15 yr of age were categorized into one stock variable (*>3-yr-old*). Further separation by age class was of limited value because of the variability in production and the lack of conclusive findings on how longevity is affected by EW calves on primiparous cows. No decrease in PPI (*EW PPI reduction*) was included in the EW and CW comparison. If no reduction of PPI was included in the EW scenario, the likelihood of increasing *>3-yr-old pregnancy rate* or decreasing *average >3-yr-old cull rate* became minimal.

Calf Production Compartment. The calf portion of the model (Table 2; Figure 3) uses the cow production to aggregate the number of calves produced on an annual basis. After the number of calves was determined, the model calculated the age of the calves by using the *days weaned* (starting Nov. 12) and the *average day conceived* for the given year. The *weaning weights* were then determined using an estimated ADG for either EW or CW management practice. The *number of first calves* were subjects of either EW or CW (depending on the experiment, described below) and therefore were subject to alternative management practices. If the *days weaned* was less than the earliest *date to ship first calves to stocker* location, then the calves were subject to a period of *days held in*

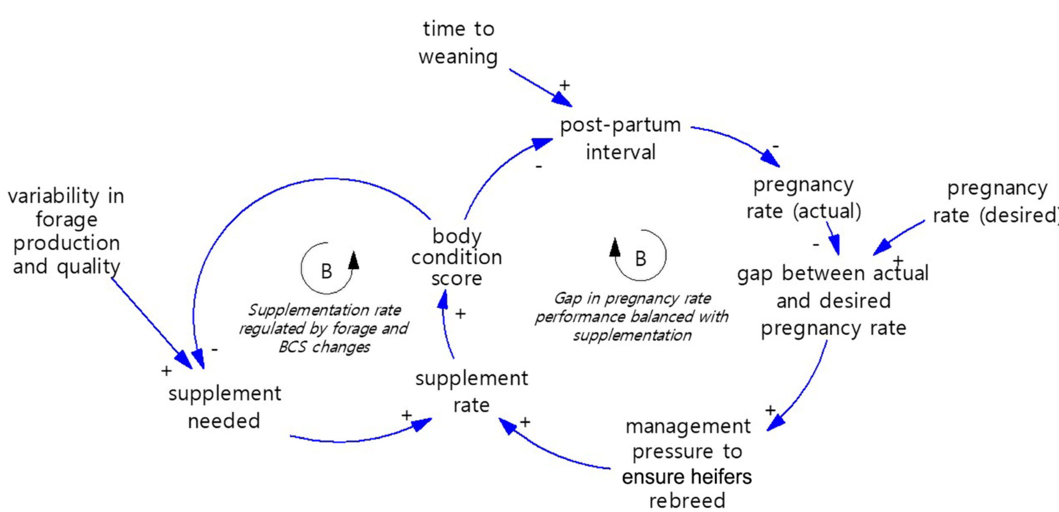

Figure 1. A visual representation of the causal loop diagram constructed from the dynamic hypothesis, from which variables have been developed to illustrate the key relationships believed to be at work in the problem at hand. Arrow heads are accompanied by either a "+" or "–." When a "+" is present, the target variable is expected to change in the same direction as the source variable. For example, as *supplement rate* increases, *body condition score* also increases. Conversely, when *body condition score* decreases, the *postpartum interval* required for successful pregnancy increases (shown by the "–" sign). The "B" at the center of each loop indicates a negative- or balancing-feedback loop process, in which a change in one variable feeds back to balance out or oppose the effect of the initial change.

Table 1. Central equations for the cow production line[1]

Variable	Equation				
Yearlings conceived in allotted time	= number of capitalized replacements × replacement pregnancy rate × percent conceived in allotted − progression to eligibility × (1 – cow death rate)				
2 yr olds eligible for EW	= progression to eligibility – 2-yr-old open rate – progression to commercial herd				
Open 3 yr old	= 2-yr-old open rate – 4-yr-old pregnant opens – culled 3 yr olds – number of open 3-yr-old deaths				
Pregnant 3 yr olds	= progression to commercial herd – 3-yr-old open rate − number 3-yr-old deaths – progression to mature cow herd				
Open 4 yr olds	= 3-yr-old open rate – 5-yr-old pregnant opens – culled 4 yr olds – number of 4-yr-old open deaths				
>3-yr-old cows	= 4-yr-old pregnant opens + 5-yr-old pregnant opens + progression to mature cow herd − culled >3 yr old – number >3-yr-old deaths				
BCS at calving	= IF days weaned > days fed energy, THEN BCS previous calving + (days weaned – days fed energy) × lactating cow ADG in BCS + (365 – days weaned × nonlactating cow ADG in BCS), ELSE BCS previous calving + (days weaned × lactating cow ADG in BCS) + (365 – days weaned × nonlactating cow ADG in BCS)				
BCS and pregnancy rate interaction (a lookup table function)	BCS at calving	3	4	5	6
	3-yr-old pregnancy rate	0.43	0.61	0.86	0.93

[1]Conditional statements using IF, THEN, ELSE are translated as IF (condition met?), THEN (operation if true), ELSE (operation if false). Variables correspond to major stocks, flows, and auxiliary variables in Figure 2.

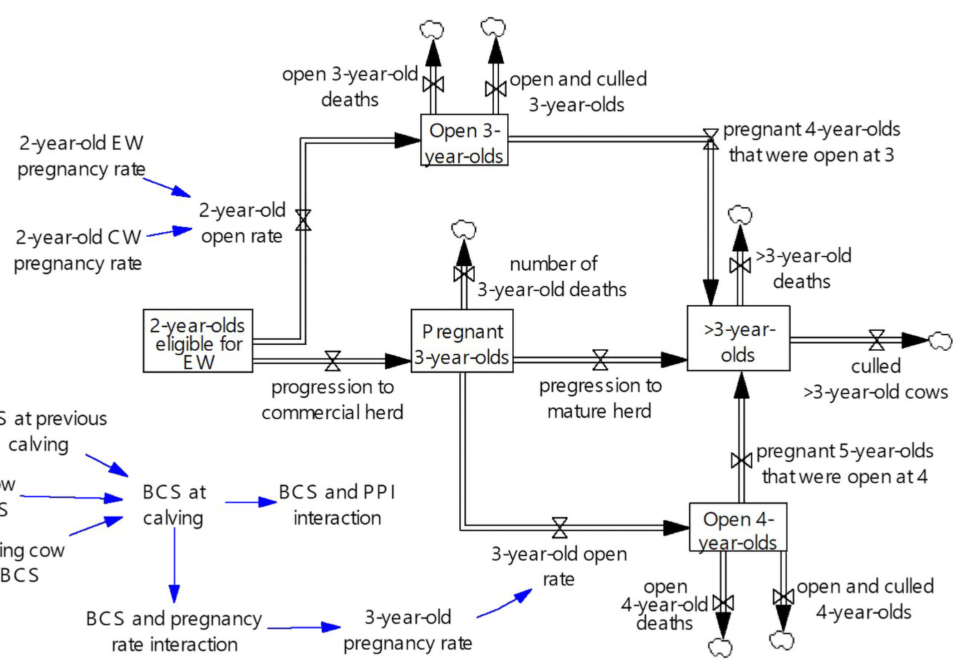

Figure 2. Simplified stock-flow model of the cow production line representing the progression of one generation of cows through the production system. Stocks represent accumulations and are illustrated by boxes. Flows represent the rate of change in the stock (i.e., change over time) and are illustrated by thick arrows into and out of the stock (i.e., inflows and outflows). Auxiliary variables represent information links, relational formulas, or decision-making criteria used to manipulate the stocks through changes in inflows and outflows. As 2-yr-old heifers are confirmed pregnant, they progress to the next stock of pregnant cows (where cows with successive confirmed pregnancies remain in the *>3-yr-olds* stock), whereas open, nonpregnant cows proceed to a stock of open cows or are culled. Variable names correspond to names used in Table 1 and Supplemental Table S1 (https://doi.org/10.15232/aas.2021-02235). EW = early weaning; CW = conventional weaning; PPI = postpartum interval.

a grow yard before stocker grazing. Otherwise, calves are weaned directly to the stocker operation. All calves were managed according to the CW system upon arrival at the stocker stage. The *number of second calves* was indirectly affected by EW, due to the *EW PPI reduction* (ranging from 0 to 21 d depending on the allotted time to become eligible for EW) and increased pregnancy rates of EW primiparous cattle [*2-yr-old pregnancy rate (EW)* of 0.93 compared with 0.82 under CW; Arthington, 2016; Supplemental Table S1; https://doi.org/10.15232/aas.2021-02235]. The *number of third calves* and *4+ calves* were also indirectly affected by EW due to the shortened PPI of the previous year, as well as the increase in *BCS at calving* resulting from early termination of lactation. For all calf crops, postweaning shipment dates were altered by using the *shipping date adjustment for the indicated year*, allowing for the manipulation of the flow of cattle out of the calf production model and into the stocker operation model depending on CW or EW scenario.

Stocker Operation Compartment. The stocker component was used to calculate the number of *days grazed as stockers* and the *total weight gained* between arrival at the stocker operation and arrival at the feedyard (Table 3). The stocker model was initiated by the *shipping date adjustment for the indicated year* (when calves enter from the calf production model) and then terminated with the associated calf crop *shipping date adjustment to feedyard* (when calves enter the feedyard). The first generation of stockers (*number of first stockers from ranch herd*) were subject to EW or CW scenarios. All generations of stockers following the first-generation calves were managed according to the CW system based on historical assumptions provided by the ranch (i.e., dates, costs, ADG, and death rate). Due to differences in arrival dates, stockers had different ADG for either scenario, EW (mean of 1.13 kg/d) or CW (mean of 0.5 kg/d; Supplemental Table S1; https://doi.org/10.15232/aas.2021-02235). For the EW scenario, stockers depart the stocker operation at different times than CW calves. Therefore, both EW and CW have shipping date adjustment variables (*shipping date adjustment to feedyard for EW* or *shipping date adjustment to feedyard for CW*) to properly flow cattle to the feedyard model.

Feedyard Operation Compartment. The feedyard model replicated 2 portions similar to the stocker opera-

Table 2. Central equations for calf production segment[1]

Variable	Equation
Number of first calves[2]	= IF days weaned <91, THEN 2 yr olds eligible for EW × [replacement heifers EW rate (per pregnant)] ELSE 2 yr olds eligible for EW × [replacement heifers CW rate (per pregnant)]
Days of age (first calves)[2]	= days weaned – average day conceived in yearling breeding season
Earliest date to ship first calves to stocker location	= 155[3] + EW shipping date adjustment for first calves
Days held in grow yard before stocker grazing	= IF days of age (first calves) <1, THEN 0, ELSE IF days weaned > earliest data to ship first calves to stocker THEN 0 ELSE IF days weaned < earliest date to ship first calves to stocker THEN earliest date to ship first calves to stocker – days weaned
Weaning weight (first calves)[2]	= days of age (first calves) × prewean ADG (first calves) + birth weight (first calves)
Individual calf weight shipped to first stocker	= additional weight gain on annuals + weaning weight (first calves)
Weaning date for second+ calves	= 293[4] + shipping date adjustment for second+ calves
Average day conceived in 2-yr-old+ breeding season	= IF days weaned <91 THEN average day conceived in yearling breeding season – EW PPI reduction ELSE average day conceived in the yearling breeding season + BCS and PPI interaction

[1]Conditional statements using IF, THEN, ELSE are translated as IF (condition met?), THEN (operation if true), ELSE (operation if false). EW = early weaned, CW = conventionally weaned, PPI = postpartum interval.

[2]Formula duplicated with similar variable for all ages and segments (calf, stocker, and feedyard segments).

[3]Nov. 1 to Apr. 15 = 155 d.

[4]Nov. 27 to Sep. 15 = 293 d.

Table 3. Equation for variables in the stocker production segment[1]

Variable	Equation
Days grazed as stockers	= IF days weaned < earliest date to ship first calves to stocker THEN 276 + shipping date adjustment to feedyard for EW – earliest date to ship first calves to stocker ELSE 596 + shipping date adjustment for CW first stockers to feedyard – days weaned
Total weight gained as first stockers	= IF days weaned < earliest date to ship first calves to stocker THEN days grazed as stockers × ADG of spring stocker (Aug. 15) ELSE days grazed as stockers × ADG of stockers (Aug. 15 to Jul. 1)
Number of first stockers from ranch herd	= IF days weaned < earliest date to ship first calves to stocker THEN number of first calves × (1 – stocker death loss EW) ELSE number of first calves × (1 – stocker death loss CW)
Individual first stocker weight shipped to feedyard[2]	= individual calf weight shipped to first stocker × (1 − shrink to stocker location) + total weight gained as first stockers
Days grazed as second+ stockers	= 289[3] – shipping date adjustment for second calves (Sep.) + shipping date adjustment to feedyard for second calves (Jul.)

[1]Conditional statements using IF, THEN, ELSE are translated as IF (condition met?), THEN (operation if true), ELSE (operation if false). EW = early weaned, CW = conventionally weaned.

[2]Formula duplicated with similar variable for all ages and segments (calf, stocker, and feedyard segments).

[3]Sep. 2–Jul. 1 = 289 d.

tion model (Table 4). The first generation of fed cattle (*number of first fed cattle shipped to packer*) enter the feedyard at different dates that coincide with EW or CW, which affects the initial weights and *days on feed* required to reach a *finish target weight* (constant at 555 kg for EW or 590 kg for CW; Supplemental Table S1; https://doi.org/10.15232/aas.2021-02235). A separate ADG was used to accurately capture performance depending on the time on feed driven by weaning scenario (*ADG of 272-kg calves*, 1.31 kg/d, or *ADG of 363-kg calves*, 1.59 kg/d). All gen-

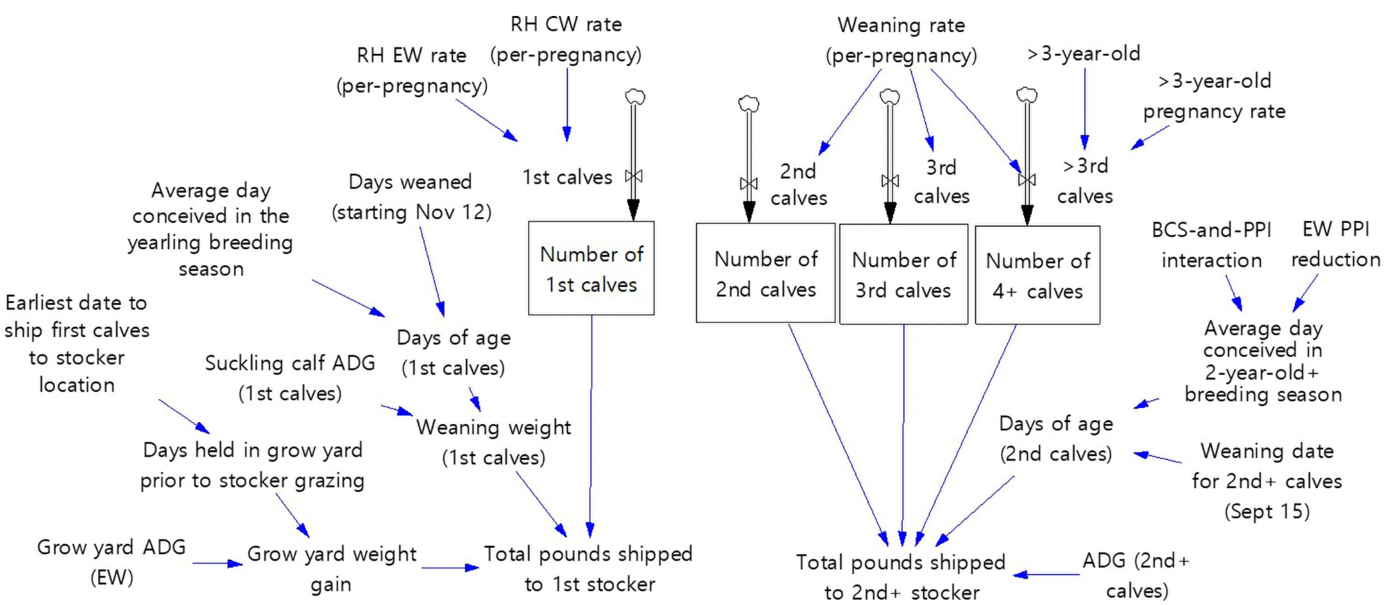

Figure 3. Simplified stock-flow model representing calf production (number of calves) and total pounds shipped from the cow-calf enterprise to the stocker enterprise for each year in the cow production model and depending on weaning strategy (early weaning = EW, conventional weaning = CW) and production interactions between BCS, postpartum interval (PPI), and ADG (RH = replacement heifer). The stocks, flows, and auxiliary variables illustrations follow the same convention as described in the cow herd dynamic. Variable names correspond to names used in Table 2 and Supplemental Table S1 (https://doi.org/10.15232/aas.2021-02235).

erations of fed cattle following the first generation (*number of second+ fed cattle shipped to packer*) were managed under the existing management practices.

Financial Compartment. Each production segment of the model included segment-specific costs of production (Table 5). All production-segment costs were composed of feed costs and rent or yardage costs, with the remainder of the cost collectively classified as other costs. The EW and CW scenarios of the first-generation calves required first-calf heifers and cows to be modeled separately in the cow-calf models. To capture the cost of EW calves on first-calf heifers, *heifer feed cost/head* included *protein supplement cost*, *mineral supplement cost*, and *energy supplement cost*, to allow *heifer energy supplement cost* to be subject to *EW feed efficiencies* for the time period after EW but before spring green up. The remainder of the first-calf heifer cost consisted of *heifer grazing rent/head*, *additional calf cost/head if EW* (i.e., grow yard costs), and all other costs were compiled into *other heifer cost/head* (i.e., depreciation, medical, supplies, and fixed cost allocation). Cow cost consisted of the same 3 input categories as first-calf heifers. The capitalized costs for both the heifers and cows were allocated across the number of calves weaned to determine individual calf cost.

The stocker cost model used the stocker compartment values to calculate the total production costs from the time of arrival at stocker operation to arrival at the feedyard. Similar to the cow-calf cost model, the stocker cost model separates the *first stocker individual costs* from stockers that are not directly affected by the EW scenario. The days in which EW and CW stockers were grazed varies in length and season, affecting the days that supplemental protein is needed. The remaining stocker generations were subject to the existing CW assumptions. The feedyard cost model totaled the *cumulative days on feed* (which varied depending on CW or EW calves in the first 2 yr) from all generations of calves to yield a *total yardage cost*. The *total weight gained at feedyard* was used to calculate total feed cost. Calves were fed up to 589.7 kg (CW) or 555.6 kg (EW) and then marketed as fed cattle. All other costs were combined in feedyard *medical and other/head cost.*

The only revenues to the system were the sale of fed cattle and cull cattle sales (determined by the *average >3-yr-old cull rate*), which together constituted the *total cumulative revenue (feedyard).* The *total cost of production* was subtracted from the *total cumulative revenue (feedyard)* to calculate the total *cumulative cash flow* for the 15 yr being modeled. The *cumulative cash flow* was subject to a *discount rate* to generate an overall *net present value* (**NPV**). Although the system only had 2 revenue sources (sales at the feedyard and cull cow sales), livestock market values were applied at each transfer point and time (e.g., calves from cow-calf to stocker segment, stockers from stocker to feedyard segment) to yield a potential revenue estimate (at each production segment) to weigh against observed costs to estimate profitability and determine NPV at each production phase (cow-calf, stocker, and feedyard).

Model Evaluation and Calibration

Before experimental simulations were conducted, the model was calibrated to the current beef production system (in collaboration with managers throughout the system) and then evaluated to measure how accurately and precisely model data matched observations (Tedeschi, 2006). The calibration phase began by building the cow production line (Figure 2), which simulated the number of cows to match the current production system, tracking one

Table 4. Equation for variables in the feedyard production segment[1]

Variable	Equation
Weight to be gained on first feeder cattle	= IF days weaned < earliest date to ship first calves to stocker THEN finish target weight EW – individual first stocker weight shipped to feedyard × (1 − shrink percentage to feedyard) ELSE finish target weight CW – individual first stocker weight shipped to feedyard × (1 − shrink percentage to feedyard)
First fed cattle finish weight	= IF days weaned < earliest date to ship first calves to stocker THEN finish target weight EW ELSE finish target weight CW
Days on feed for first fed cattle	= IF days weaned > earliest date to ship first calves to stocker THEN (weight to be gained on first feeder cattle/historical ADG of 272-kg calves) ELSE (weight to be gained on first feeder cattle/historical ADG of 363-kg calves)
Number of first fed cattle shipped to packer[2]	= number of first stockers from ranch herd × (1 – feedyard death rate for stockers)

[1]Conditional statements using IF, THEN, ELSE are translated as IF (condition met?), THEN (operation if true), ELSE (operation if false). EW = early weaned, CW = conventionally weaned.

[2]Formula duplicated with similar variable for all ages and segments (calf, stocker, and feedyard segments).

Table 5. Equation for variables in the financial model segment[1]

Variable	Equation
Yearling/cow cost	
Heifer days fed mineral	= 365 – heifer days fed protein
Heifer protein supplement cost[2]	= heifer days fed protein × heifer protein feed kg/d × heifer protein feed cost/kg
Heifer energy supplement cost	= IF days weaned < heifer days fed energy THEN [(heifer days fed energy – days weaned) × heifers energy feed kg/d × (heifer energy feed cost/kg) × (1 − EW supplement efficiencies)] + [(heifer days fed energy – days weaned) × heifer energy feed kg/d × heifer energy feed cost/kg] ELSE heifer days fed energy × heifer energy feed kg/d × heifer energy feed cost/kg
Heifer feed cost/head	= heifer energy supplement cost + heifer mineral cost + heifer protein supplement cost + heifer calf creep feed cost
Individual heifer cost	= IF days weaned < earliest date to ship first calves to stocker THEN additional calf cost/head if EW + heifer feed cost/head + heifer grazing rent cost/head + other heifer cost/head ELSE heifer feed cost/head + heifer grazing rent cost/head + other heifer cost/head
Total cumulative first calf cost	= (individual heifer cost × EW eligible) + (additional calf cost/head if EW × number of first calves)
Total cumulative 2+ calf cost[3]	= individual cow cost × {number of >2-yr-old calves × [1 − weaning rate (per pregnant)] + open 3 yr olds + open 4 yr olds}
Individual cow cost	= cow feed cost/head + cow grazing rent cost/head + other cow cost/head
Total cull cow revenue	= number of cull cows × average cull cow weight × cull cow price/kg
Stocker cost	
EW actual days supplemented	= EW days supplemented (stockers) + shipping date adjustment to feedyard for EW + EW shipping date adjustment for first calves
CW actual days supplemented	= CW days supplemented (stockers) + shipping date adjustment for CW first stockers to feedyard
Individual first stocker days supplemented	= IF days weaned < earliest date to ship first calves to stocker THEN EW actual days supplemented ELSE CW actual days supplemented
First stocker total individual feed cost/head	= individual first stocker days supplemented × stocker total protein kg/d × stocker protein feed cost/kg
First stocker individual cost	= [stocker other cost/head × (days grazed as stockers/number of CW grazed days)] + [stocker grazing rent/head × (days grazed as stockers/number of CW grazed days)] + first stocker total individual feed cost/head
Total second+ stocker feed days	= CW days supplemented (stockers) + shipping date adjustment for second+ calves
Total cumulative stocker cost	= total cumulative first stocker cost + total second+ stocker feed cost + total second+ stocker other cost + total second+ stocker grazing rent cost
Feeder cattle cost	
Individual fed cattle cost (first calves)	= (days on feed for first fed cattle × yardage/head per day) + (weight gained on first fed cattle × feed cost/kg gain) + medical and other/head
Financial analysis	
Total cost of production	= [total cumulative cost (feedyard) + total cumulative stocker cost + total cumulative cow cost + total cumulative heifer cost]
Total cumulative revenue at feedyard	= [(total weight of fed cattle × feedyard sale price/kg) + total cull cow revenue]
Net present value	= {(Total cumulative revenue at feedyard – Total cost of production)/ $[(1 + \text{discount rate})^{\text{time period}}]$}

[1]Conditional statements using IF, THEN, ELSE are translated as IF (condition met?), THEN (operation if true), ELSE (operation if false). EW = early weaned, CW = conventionally weaned.

[2]Formula duplicated with similar variable for all heifer supplement costs.

[3]Formula duplicated with similar variable for all cow costs.

generation of heifers through the end of their productive life (Supplemental Figure S1; https://doi.org/10.15232/aas.2021-02235). Model outputs were compared with historical values for first-calf and total ranch average weaning weights; stocker and feeder cattle arrival and departure weights; as well as weight gain of calves, stockers, and fed cattle. After calibrating the model to match the behavior of the current CW production practices (Supplemental

Table S2; https://doi.org/10.15232/aas.2021-02235), EW scenarios were modeled and analyzed against CW.

Experimental Simulations: What-If Scenario and Sensitivity Analyses

Revenues were generated once fed cattle were sold out of the production system. Costs were accounted for at each component of the system, which included a transfer cost of livestock (i.e., the market value of the animal had it been sold following the weaning or stocker phase, such that each enterprise could be evaluated independently). Management required a 5% internal rate of return (**IRR**) for potential investments or changes in the production system to be considered. [Internal rate of return is that discount rate in which NPV of future cash flows would be $0, making the decision maker indifferent to the investment. Internal rate of return values greater than interest rates (or opportunity costs of capital) yield favorable investment decisions, whereas those values less than interest or cost of capital yield negative NPV or undesirable investments.] Prices were compiled from CattleFax projections for 4- and 5-weight steers, and live cattle were used. A price slide of $13/hundredweight (**cwt**, = 45.36 kg) between 4-weight and 5-weight steers were used to determine prices for a 3-, 6-, and 7-weight steer. Prices were then discounted $3/cwt from the steer price to find an average steer and heifer price. In collaboration with management, we formulated 2 testable hypotheses useful for meeting our objectives:

1) EW would enhance cow-calf profitability through improved reproductive efficiency of primiparous replacement heifers, which would improve overall performance (measured as total calf production) as replacement heifers matriculate into the cow herd (objective 1); and
2) EW would improve profit performance of the integrated beef production system due to increased calf production at the cow-calf level (objective 2).

To test each hypothesis, several what-if analyses were performed that affected both production and financial model components. These included 2 scenarios in which adjustments were made to the *average day conceived in the yearling breeding season*, a critical variable influencing the allotted time given to be eligible for EW (i.e., calves born too late in the system would not meet the required minimum age of 70 d at time of EW). By adjusting the *average day conceived in the yearling breeding season*, the number of 2-yr-old replacement heifers that calve within a specific interval to start the calving season (21 d and 42 d, respectively) and are therefore eligible for EW were estimated. Current management estimated that the *average day conceived in the yearling breeding season* was 10 to 11 d (for yearling replacement heifers) and 24 d (for primiparous replacement heifers).

In scenario A (qualifying replacement heifers calving in the first 21 d of the calving season), the applied value for *average day conceived in the yearling breeding season* was 10.5 d, whereas in scenario B (qualifying replacement heifers calving in the first 42 d of the calving season), assumptions about average day conceived were relaxed to 21 d. In both scenarios the average weaning date of primiparous replacement heifers varied depending on the treatment (CW at 276 d or EW at 90 d), and all other assumptions remained the same. Model data collected from each what-if scenario included key reproductive factors (*BCS at calving*, *pregnancy rate*, *PPI*), beef production characteristics (*calf weaning weights*, *feedyard gains*, *total number of fed cattle*), or performance metrics (total number of fed cattle per EW replacement heifers) directly influenced by replacement heifer management. Additionally, the costs of livestock gains and the change in NPV of production between EW and CW strategies attributed to each production system component (cow/calf, stocker, feedyard) were collected to examine the net benefit or cost from changing weaning strategy. The annual NPV difference between CW and EW was treated as an incremental financial gain or loss from which a separate investment NPV and IRR were calculated to estimate the net benefit/cost to the system resulting from implementing EW.

To test our second hypothesis, sensitivity analyses were performed on specific replacement heifers and calf variables, including *2-yr-old EW pregnancy rate*, *feedyard sale price*, *EW calf ration cost/kg* during time in the grow yard before the stocker stage, *individual heifer cost*, and *average >3-yr-old cull rate.* Each variable was adjusted between ±5 and ±30% depending on the variable of interest (Table 6), and *days weaned* was set to either 90 d (EW) or 276 d (CW). Once ranges of uncertainty were assigned, the model was run 1,000 times. This sensitivity analysis method was intended to identify over which parameter space ranges the resulting cost–benefit outcomes (directly measured through the NPV of the system as well as each component) would be favorable or unfavorable to management. By identifying significant parameters leading to favorable or unfavorable outcomes, the model analysis facilitated identification of which replacement heifer management factors, input costs, or production output prices either escalated or mitigated economic risk to the integrated production system and whether EW would improve overall economic performance.

RESULTS AND DISCUSSION

What-If Scenarios A and B: 21-d and 42-d Allotted Calving Window for EW Potential

Scenario A (21-d allotted calving time) produced small but important differences in production and financial outcomes between CW and EW (Table 7). By EW calves of primiparous cattle, *2-yr-old pregnancy rate* increased 11%

and BCS increased almost 1.5 units before the next calving season compared with CW. This increase in pregnancy rate increased the number of calves per exposed female, equating to a total of 864 more fed cattle in the system, such that the *total number of fed cattle per 2-yr-old eligible for EW* increased from 6.05 for CW to 6.40 for EW. Conversely, *weaning weights of first calves* decreased by almost 300 lb (or 136 kg), causing the cost per weight gained at the cow-calf level to escalate from $119 to $161 per cwt (or $2.62 to $3.55 per kg), a 35% increase. Despite increased costs, EW calves from one generation of replacement heifers proved to be a profitable management practice, as EW outperformed CW by $37,788, yielding an IRR of 7.8% (Table 7), indicating a financially attractive option that met management's minimum rate of return criteria.

Scenario B differed from scenario A in that the allotted time of 42 d allowed PPI to decrease by 17 d, observed in the *average day conceived in breeding season 2* (23.7 vs. 6.2 for CW and EW cattle, respectively). The model forecasted that the 17.5-d reduction in average day conceived in breeding season 2 resulted in a 7.1% decrease in *average >3-yr-old cull rate* and a 1.2% increase in *>3-yr-old pregnancy rate.* This allowed cows to stay in the herd longer and increase the *number of fed cattle per 2-yr-old eligible for EW* from 6.05 to 6.61 for CW and EW (Table 7). This 0.56 increase in *number of fed cattle per 2-yr-old eligible for EW* equates to 1,362 additional calves produced over the 15 yr modeled, compared with the scenario A estimate of 863 extra calves (Figure 4), demonstrating the long-term effects of keeping cows in the herd longer. Scenario B likewise showed EW to be a profitable management practice as EW outperformed CW by a difference of $255,617, equivalent to a 28% IRR (Table 7), well surpassing management's required return rate and indicating the superior of the 2 EW options.

Sensitivity Analyses: Cost–Benefit Analyses of Altering Replacement Heifer Factors

Altering the specific replacement heifers and calf parameters created noticeable changes in the number of *>3-yr-old cows* (Figure 5a; an ending range between 172 and 516 cows) and their associated *total calves produced* (Figure 5c; an ending range between 13,659 and 16,914). Financially, returns to the cow-calf component were shown to be the least susceptible to changes in replacement heifer dynamics and costs of production (Figure 5c), followed by the stocker (Figure 5d) and then feedyard components (Figure 5e). Analysis of the correlation coefficients of the test input variables revealed several critical variables that contributed the majority of the influence on key system variables (see Supplemental Material and Supplemental Figure S1 for additional description of the sensitivity procedure and results; https://doi.org/10.15232/aas.2021-02235). Contrary to our initial hypothesis, reducing *days weaned* led to immediate reductions in cow-calf returns. Interestingly, the stocker component benefited the most from reductions in *days weaned* or increases in *allotted time* for qualifying EW replacement heifers (Figure 5d). The feedyard component showed tremendous risk of loss due to changes in finished cattle prices and was insensitive to all other variables tested (Figure 5e). The benefit of EW to total NPV occurred in the first year, with subsequent years showing little to no increase (Figure 5f). *Feedyard sale price* was the most influential factor on total NPV, with the majority of simulation runs producing negative financial returns (Figure 5e).

Effects of EW versus CW on Individual Components Within the Integrated Beef Production System

Analysis of the individual production segments showed that each enterprise was most sensitive to market prices. Most importantly, EW was profitable for the production system as a whole but did not outperform CW at all segments (Table 7). At the cow-calf level, the model predicted a reduction in NPV, from $3,594,583 for CW to $3,541,347 for EW under the 21-d allotted calving time. The stocker segment showed a NPV improvement under EW, from $158,491 to $253,868 due to cost-effective gains, which were a function of lighter arrival weights and increased days grazing. In the feedyard segment, NPV of CW was −$196,779, slightly greater than the NPV of

Table 6. Sensitivity analysis for key assumptions used to determine early-weaning (EW) economic feasibility

Parameter	Initial value	Minimum	Maximum
2-yr-old EW pregnancy rate	0.93	0.78	0.97
Allotted time (days)	42	21	42
Base >3-yr-old cull rate	0.14	0.1	0.18
Days weaned[1] (starting Nov. 12)	276	90	276
Feedyard sale price [$/lb ($/kg)]	1.25 (2.75)	1.06 (2.33)	1.44 (3.17)
EW calf ration cost [$/ton ($/kg)]	350 (158)	245 (111)	455 (206)

[1]Days weaned represents the age of calf at the time of weaning event.

Table 7. Comparisons between conventional weaning (CW; 276 d) and early weaning (EW; 90 d) under scenario A (qualifying replacement heifers for EW in the first 21 d of the calving season) and B (qualifying replacement heifers for EW in the first 42 d of the calving season) with resulting effect on production and financial components

	Scenario[2]					
	A			B		
Variable[1]	**CW**	**EW**	**Δ**	**CW**	**EW**	**Δ**
Production metrics						
2-yr-old EW pregnancy rate (%)	82	93	11	82	93	11
3-yr-old pregnancy rate (%)	82	93	11	82	93	11
>3-yr-old pregnancy rate (%)	82	82	—	82	83	1
BCS at calving	4.84	6.16	1.31	4.84	6.16	1.32
EW PPI reduction (days)	—	—	—	15	15	—
Average day conceived in yearling breeding season (days)	10.5	10.5	—	21	21	—
Average day conceived in breeding season 2 (days)	13.2	10.5	(2.7)	24	6	(17.50)
Average >3-yr-old cull rate (%)	14.00	14.00	—	14	13	(1.03)
Weaning weight first calves (kg)	224	93	(131)	217	85	−132
Individual first stocker depart weight (kg)	377	262	(115)	370	254	−116
Weight gained at feedyard (kg)	224	302	78	231	309	78
Total number of fed cattle per 2 yr old eligible for EW (head)	6.05	6.40	0.35	6.05	6.61	0.56
Total number of fed cattle (head)	14,732	15,597	864	4,732	16,095	1,362
Financial metrics						
$/kg gain cow-calf	2.62	3.55	0.93	2.71	3.73	1.01
$/kg gain stocker	1.54	0.66	(0.88)	1.54	0.66	(0.88)
$/kg gain feedyard	1.92	1.96	0.04	1.92	1.96	0.04
Total $/kg gain	2.14	2.47	0.33	2.16	2.49	0.33
First-calf heifer cost ($)	588	581	(7)	588	581	(7)
NPV ($ million)	3.939	3.977	0.038	3.842	4.098	0.255
Replacement IRR (%)	—	—	7.8	—	—	28

[1]NPV = net present value, IRR = internal rate of return, PPI = postpartum interval.

[2]Δ calculates the change in each metric moving from CW to EW.

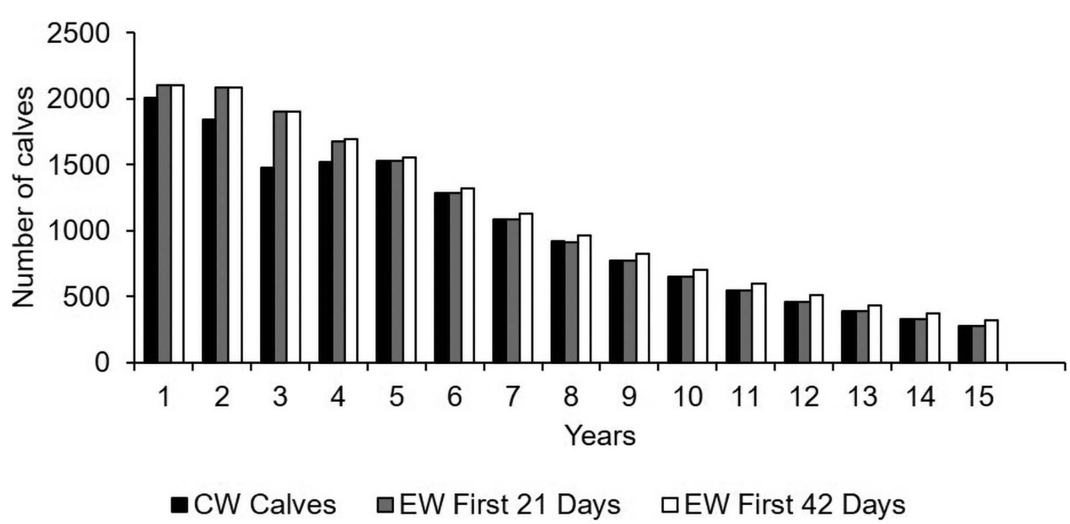

Figure 4. Comparison of conventional weaning (CW) with early weaning (EW) the first-calf heifers that calve in the first 21 d (scenario A) and 42 d (scenario B) of the calving season, and the effect over 15 yr of calves that flow through the integrated production system.

EW, −$214,374. Under the 42-d allotted calving time scenario, both cow-calf and stocker profits improved by $83,000 each with EW, whereas feedyard NPV declined to −$237,906, due to the required increased days on feed needed to reach desired finished weights. Mean differences between CW and EW showed the majority of the added returns were accounted for at the stocker rather than the cow-calf segment, whereas CW was the most beneficial for the feedyard. Across the entire system, EW was more profitable than CW, and across all segments of production, the cow-calf segment was the most profitable regardless of weaning approach.

Management Insights Generated Through the Systems Approach

Beef production systems, like the integrated ranching system studied here, can be difficult to understand and

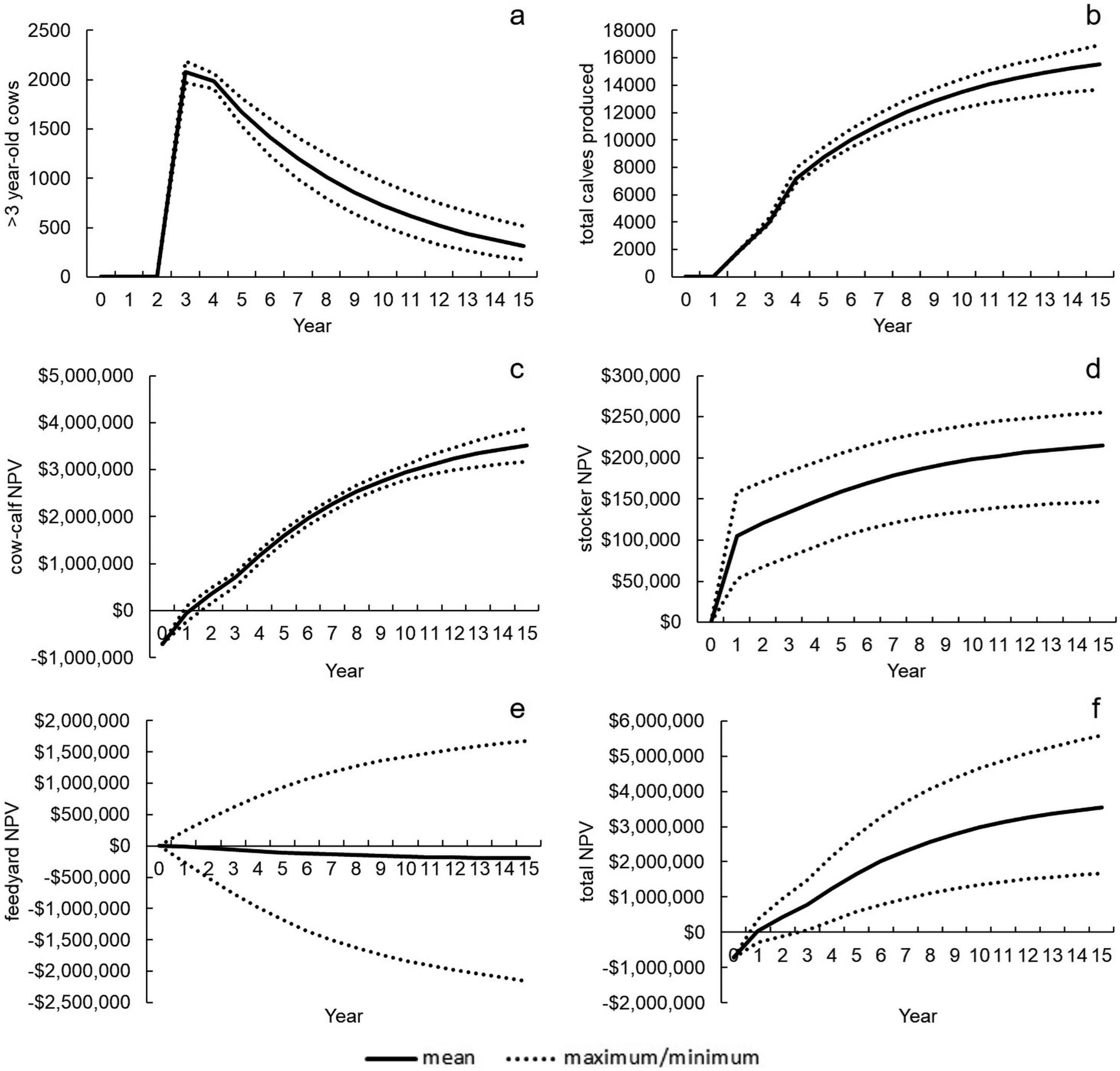

Figure 5. Mean, maximum, and minimum behavior patterns of dependent variables used in 1,000 sensitivity simulations, including *>3-yr-old cows* (a), *total calves* produced (b), *cow-calf NPV* (c), *stocker NPV* (d), *feedyard NPV* (e), and *total NPV* for the integrated system (f). The mean line illustrates the average value across the sensitivity runs, and the minimum and maximum lines illustrate the minimum and maximum values at each point in time during the simulation from time = 0 to 15 yr. Parameter values used as sensitivity inputs for the analysis are provided in Table 6. NPV = net present value.

manage due to the dynamic complexity arising from the feedback between system components (i.e., animal reproduction, forage quality, grazing and feedyard management; cash flow; and human resources; Glasscock et al., 2005; Teague et al., 2008; Turner et al., 2013; Nicholson et al., 2019; Tedeschi, 2019; Tinsley et al., 2019). The systems approach is a valuable tool useful for identifying leverage points capable of creating system change or mitigating unintended consequences from decision-making policies (Turner et al., 2016b, 2017). Leverage points are places in a system where applying minimal force or change creates significant effects on the system as a whole (Meadows, 2010). Leverage points in ranching systems often include adjustments to stocking rates, selection for improved cowherd genetics, or planning processes to cope with uncertainties (e.g., drought, marketing, or family and business transition planning).

In integrated beef production systems, such leverage points may be more difficult to employ due to ownership considerations (e.g., equity) that transcend individual production component considerations. For example, a drought plan to alleviate pressure on forage resources at the cow-calf level may result in significant stocking rate adjustments via culling, an effective strategy in standalone cow-calf enterprise. Forage resources are conserved and, although revenue potential is reduced in the short term due to reduction in animal numbers, so are the variable costs that would normally be incurred. In an integrated system, such a strategy is more difficult to justify because the cost structure extends beyond the cow-calf level, therefore so are the costs per animal that have to be covered to break even financially. Another example is a traditional feedyard where managers may manipulate average days on feed in response to ration costs by altering the timing of livestock purchases and sales. In an integrated system, delaying the point in time that livestock enter the feedyard would have feedback effects on stocker and cow-calf levels that have to retain those cattle for longer time periods causing increased forage demand. This would further exacerbate drought management or recovery and, if relied upon in the long term, could create more severe unintended consequences to the forage-based components of the system (e.g., overgrazing preferred forage species, soil compaction, and erosion).

The EW hypotheses tested above represented potential leverage points to the integrated production system not previously explored. One of the benefits of EW is the reduction in PPI, which facilitates earlier conception time and increased conception rates, thereby reducing culling rates and extending the number of productive cow years in the herd. It was hypothesized that greater productivity at the cow-calf level would provide wider ranging benefits to the integrated system as a whole. This logical causative reasoning, in which improvement in the function of one component improves the function of the whole system is not uncommon in many decision-making contexts (Senge, 1990; Cronin et al., 2009). In complex systems, misperceptions of feedback (characterized by nonlinear and time-delayed relationships) often distort learning and thwart management adaptation due to oversimplified cognitive maps (mental models) relative to real-world systems, including agricultural systems (Turner et al., 2020). Unfortunately, this plagues our ability to properly infer cause-and-effect relationships in all but the simplest systems (Cronin et al., 2009).

Overall, the model failed to reject the hypothesis that EW would improve profit performance of the integrated production system (hypothesis 2), but interestingly, it was not because EW enhanced the profitability of the cow-calf component (hypothesis 1). In fact, although EW did increase productivity (measured by total calf production) and achieved greater total financial returns compared with the conventional weaning (CW) strategy, cow-calf profitability did not improve because EW significantly reduced weaning weights (Table 7), one of the most influential factors in cow-calf revenue potential. Neither did the increase in calf production improve the financial returns at the feedyard level, because days on feed and cost of gain both increased. The financial benefit to the system from EW was captured at the stocker level (Table 8) due to the reduction in cost of gain associated with improved performance given the lighter incoming weaning weights from the cow-calf level (Table 7).

Although these results were consistent across both replacement heifers reproductive management options (scenarios A and B), scenario B achieved greater system-wide benefits. Under scenario A, replacement heifers that calved in the first 21 d of the calving season were most likely to have conceived early in the yearling breeding season. In addition, they were also most likely to become pregnant early in their second breeding season, making them less likely to be culled, leaving little margin for improvement in reproductive performance. On the other hand, qualifying first-calf replacement heifers for EW in the first 42 d of the calving season improved lifetime calf production (+1,400) because it captured the maximum number of replacement heifers that could feasibly remain on the 365-d calving interval goal (Figure 4; Table 7).

Current operational procedures provided incentives for managers in this system to maintain and enhance the metrics of their respective enterprises (e.g., cow-calf managers are rewarded based on pregnancy rates, weaning rates and weights, and cow-calf profitability; stocker and feedyard managers are rewarded based on minimizing death loss and maximizing ADG and profitability). Early weaning was thought to be a novel strategy to improve system-wide performance. Switching from CW to EW merely shifted the relative economic efficiency (and therefore the perceived effectiveness of management and resource allocations) among cow-calf, stocker, and feedyard components, an affect that would not have been observable without a model that reflected the integrated nature of the ranching system. As illustrated in these trade-offs, EW was actually an unattractive option (Figure 6) because EW improved

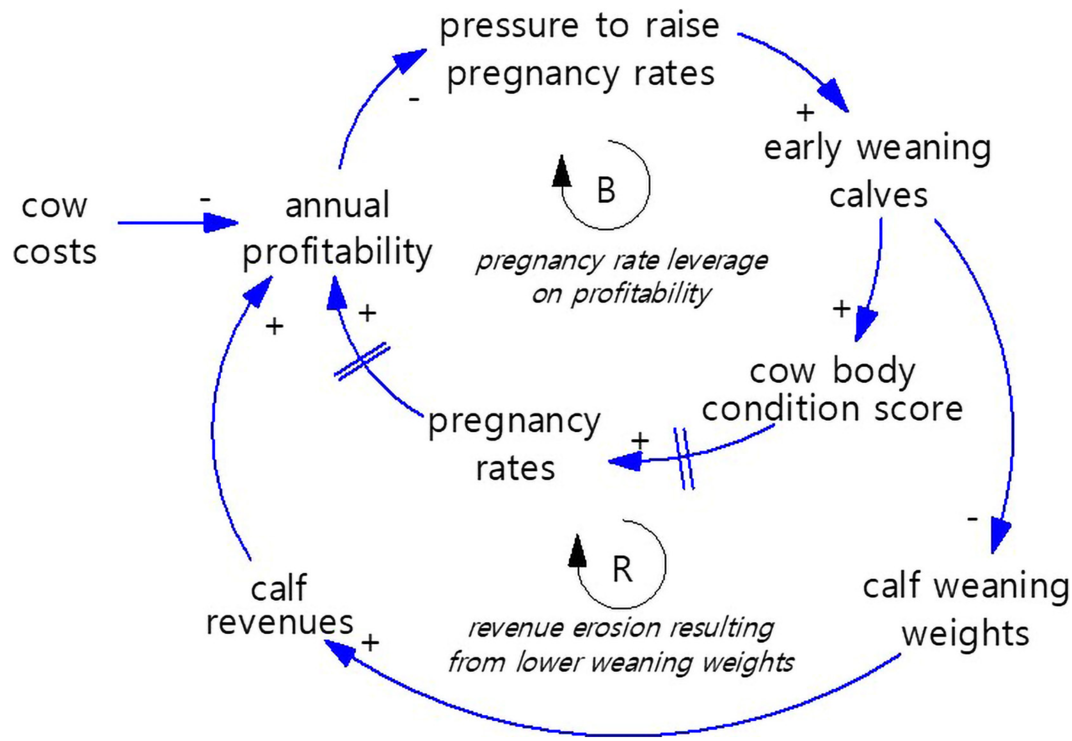

Figure 6. A "fix that backfires" relationship that may arise by early weaning calves in response to profitability pressures. Arrow heads are accompanied by either a "+" or "–." When a "+" is present, the target variable is expected to change in the same direction as the source variable, whereas a "–" indicates change in the opposite direction. For example, the pressure on annual profitability is created by the difference between calf revenues (which cause profit to increase or decrease in sequence with revenues) and cow costs (which decrease annual profitability as cow costs rise). Profit pressure may be relieved in the short term by early weaning calves, which improves cow BCS and pregnancy rates in the subsequent breeding season (which acts as a balancing leverage point, indicated by the B, center loop). However, early weaning may reduce weaning weights, the most influential factor in calf revenues, which would further erode revenues and reinforce the annual profitability pressure (indicated by the R, bottom loop).

pregnancy rates and cow longevity (which either add variable costs or reduce cull cow sales), and weaning weights (the primary determinant of cow-calf profitability) were greatly reduced, which would further stress annual profitability concerns. Adding to this complexity is the variability of cattle market prices that provided the value of transfer values used to evaluate the efficiency of each segment. Market dynamics could therefore mislead managers by pressuring the system to respond to changes in cash flow occurring at the feedyard segment. Potential adjustments at the cow-calf and stocker levels, given particular transfer costs, could reduce their perceived economic efficiency.

Managing myopically (or "in silos") tempts managers to confront symptoms rather than root causes of problems (Senge, 1990; Ackoff, 1994). When examining the

Table 8. Profitability comparison of segment net present value (NPV) for conventional-weaning (CW; 276 d) and early-weaning (EW; 90 d) scenarios produced under multiple parameter sensitivity analysis [2-yr-old EW pregnancy rate; allotted time, days (in breeding season); base >3-yr-old cull rate; days weaned; feedyard sale price, $/kg; EW calf ration cost, $/kg], all other parameter values being equal

	Production system segment			
Weaning strategy	Cow-calf NPV ($)	Stocker NPV ($)	Feedyard NPV ($)	Cumulative NPV ($)
CW	3,594,583	158,491	(196,779)	3,556,295
EW (21-d allotted calving time)	3,541,347	253,868	(214,374)	3,580,841
EW (42-d allotted calving time)	3,678,560	245,883	(237,906)	3,686,536
Difference in CW and mean of both EW strategies	15,370	91,384	(29,360)	77,394

root cause of the problem in cowherd reproductive performance, the issue is a function of the variability and quality of forage production (Figure 1), which would be better addressed through investments in improved pastures rather than specific livestock management practices. This poses a unique challenge to managing the system as a whole, because interrelationships between components have not been well quantified nor reported to account for trade-offs or synergies between cow-calf and stocker, stocker and feedyard, and cow-calf and feedyard segments. Given that managers are rewarded based on the success of their respective segment relative to the entire system, implementing a strategy such as EW could cause longer-term problems in the ability of the ranch to address the root problem with pasture improvements. For example, EW benefited the system as a result of the gains accrued at the stocker segment rather than the cow-calf or feedyard. This immediate financial feedback masks the contribution of the change in cow-calf management to whole-system performance, which could lead to disproportionate annual rewards to the stocker rather can cow-calf segment. This unintended consequence may limit resource acquisition needed for long-term investments at the cow-calf level (such as improved pastures) and would shift the burden of meeting production expectations solely to short-term livestock management adjustments (Figure 7).

Finally, it is important to highlight the most important input parameter identified for the integrated system: *feedyard sales price.* Because all cattle revenues were generated at the end of the production line, *feedyard sales price* was the most influential factor on feedyard NPV and total NPV (Figure 5e and 5f). Over the entire simulation range, average feedyard NPV was just below zero (breakeven), ranging from almost \$2.5 million in loss to almost \$2 million in profit (Figure 5e). Likewise, total NPV, ranged from \$1.6 million to \$5.5 million, the variation of which was explained almost entirely by *feedyard sale price* (Supplemental Figure S2; https://doi.org/10.15232/aas.2021-02235). Given the importance of this factor, the integrated system was exposed to tremendous price risk given the uncertain variation in commodity prices, influenced by existing supply and demand, future expectations, financial markets, and international trading (e.g., tariffs and dumping), among other factors. Therefore, it is critical that cost control, marketing, and risk management functions become essential organizational functions to reduce price risk exposure given the potential financial threat it could become during unfavorable price movements. As discussed above, manipulating the flow of cattle through the production system may not hold as much potential to manage profitability as originally anticipated due to the trades-offs in relative gains or losses between individual production segments.

Model Strengths, Weaknesses, and Possible Extensions

In general, the model was able to capture the various segments of the integrated beef production system, but several improvements could be incorporated to better

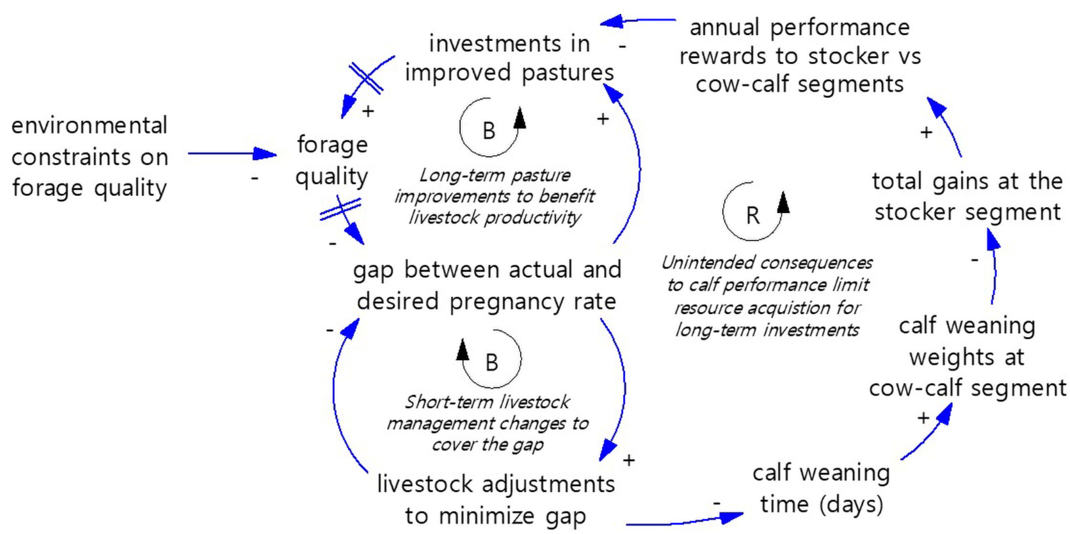

Figure 7. A "shifting the burden" situation that may arise due to the trade-offs in the production system and incentive structure given to managers. Arrow heads are accompanied by either a "+" or "–." When a "+" is present, the target variable is expected to change in the same direction as the source variable, whereas a "–" indicates change in the opposite direction. For example, increasing the gap between actual and desired pregnancy rates would call for greater investments in improved pastures (in the long term) or livestock adjustments to minimize gap (in the short term), either of which aims to reduce the gap (both balancing processes, indicated by the B in center loops). However, the unintended consequence of relying on livestock adjustments such as reducing the calf weaning time leads to smaller weaning weights at the cow-calf segment and greater gains at the stocker segment. Due to the incentive structure, annual performance rewards may be disproportionate in favor of the stocker enterprise and fewer resources being allocated to the cow-calf enterprise to invest in improved pastures. If left unaddressed, the burden of closing the reproductive performance gap is shifted to the short-term solution of livestock adjustments that managers are forced to rely on.

represent more detailed pasture, forage, and feedyard dynamics. The current model boundary incorporated only livestock population, costs (including the costs of grazing), and revenues but did not include detailed pasture or forage components needed to explore the vulnerability of the system to environmental threats (droughts). The feedyard component did not include a detailed stock-flow chain (like that of the cow-calf segment) needed to model the progression through the feedyard from placement to finishing. This would be needed to simulate animal progression through the feedyard from placement to finishing. It would also allow for exploration of various risk management and marketing strategies in light of the importance of *feedyard sale price* to the entire production system. Last, due to data-sharing restrictions placed on managers, calibration and evaluation were solely done with point predictions rather than behaviors over time. Increasing data availability could have increased confidence in the calibration. Fortunately, given the model's consistency in matching real-world behavior, this likely would not have significantly altered the insights discussed above.

APPLICATIONS

These results imply that although early weaning (EW) enhanced profitability of the integrated production system, it was not because of the hypothesized reason involving improved cow-calf profitability. Counterintuitively, EW reduced both cow-calf and feedyard profitability, but these losses were overcome by economic gains in the stocker segment, driven by more efficient gains because calves entered the stocker level at lighter BW. Additionally, feedyard sale price (the price received for finished cattle) was the most influential exogenous factor on financial returns, highlighting the need for effective marketing and risk management functions to reduce price risk exposure.

Like any business, the goal of this beef production system was to maximize economic returns. As such, managers were tasked with making decisions to improve the whole production system; however, organizational incentives rewarded managers for maximizing economic efficiency at each segment of the enterprise evaluated independently of the other segments. Results of simulation experiments illustrated a key trade-off among the cow-calf, stocker, and feedyard segments arising from adoption of EW. The reduction in calf weaning weights facilitated more efficient gains at the stocker segment and resulted in lighter placement weights at the feedyard. This may provide misleading organizational feedback regarding successful management and cause disproportionate rewards to accrue to one segment over another. In the case of the cow-calf segment, the unintended consequence of improving cow-calf returns may lead to a reliance on short-term livestock adjustments, a behavior known as "shifting the burden." Learning how to expand management mental models to better recognize, account for, and manage such trade-offs remains an important area for future work.

The unique system studied also illustrated why it is so difficult to integrate a beef production enterprise from cow-calf through finishing stages. Awareness of trade-offs and synergies between segments is a critical first step in designing an integrated beef enterprise but management efforts remain myopic unless incentives reward managers for working across boundaries and with other leaders throughout a given system. A holistic approach provides insights about the effectiveness of management changes in one particular livestock segment and how those changes can affect the integrated supply chain.

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ORCIDS

Benjamin L. Turner https://orcid.org/0000-0003-1312-2421