The Impact of Beef-on-Dairy on the Beef Supply Chain and Potential Revenue Implications for Dairy Producers: A Market Analysis and Price Integration

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Abstract

The practice of breeding dairy females to beef bulls to create Beef-on-Dairy (BxD) offspring has become an increasingly popular topic. For dairy producers, this can add value to cattle that are not retained as replacement females. Within the U.S. beef supply chain, BxD cattle can offer a consistent supply of quality feeder calves and can help offset the current tight national feeder calf supplies of traditional beef. The purpose of this research is to better understand the impact that BxD has on both the beef and the dairy industries in the U.S. In the first chapter, "The Presence of BxD Cattle in the Beef Supply Chain," we conducted a market analysis of BxD, estimated the number of BxD cattle in the U.S. beef supply chain, and calculated Pearson correlations between our headcount estimate and data from USDA reports. Results from chapter one suggest approximately one quarter of cattle placed on feed in 2025 were BxD. Compared to our annual estimate of BxD headcount, we saw strong positive correlations with the number of cattle grading prime and the number of yield grade 5s. In chapter 2, "Price Integration and Market Leadership of BxD Markets," we evaluated price relationships between 18 BxD markets across the U.S. and identified price leaders and followers of BxD pricing. We found 10 cointegrated relationships across the U.S. based on currently available data. Of these markets, three were identified as price leaders at the 5% significance level. These findings help inform producers and other industry stakeholders on the current and future impact of BxD cattle in the beef supply chain.

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Chapter 1: The Presence of Beef-on-Dairy Cattle in the Beef Supply Chain

Introduction

An annual decision that dairies must make to maintain an optimal dairy-producing herd is how many females to replace in their milking herd. Multiple factors, including milk price, replacement female price, cost of production, cull rate, and future operational goals, affect the producers' annual decision regarding the number of females to retain or replace (Groenendaal et al., 2004). If a dairy producer needs replacement females, they can either develop their own or buy replacement females. With each annual calf crop, a dairy producer decides on the percentage of the heifer calf crop that they will retain as replacement females. This percentage can change every year, but it is never 100% of the heifer crop. The remaining share of females not retained is either sold to other dairy operations as replacement females or sold as feeder calves. Additionally, within each annual calf crop, there are also males that are sold as feeder calves. Thus, there are males and females that are sold each year by dairy producers as feeder calves (Poock & Beckett, 2022).

Producers often use high-quality sexed dairy semen to produce their desired number of replacement females, leaving the producer with a decision regarding how to breed the remainder of the cow herd (De Vries et al., 2008; Pereira et al., 2022). Historically, the objective for these cows was to maintain high conception rates, regardless of sire selection, to stay on their milk production schedules. However, recent shifts in two concurrent markets have fundamentally altered the structure of dairy herd management. First, prices for bred heifers have declined, reducing the financial incentive for producers to develop replacement females beyond what is operationally necessary. Second, the widespread adoption of sexed semen technology has allowed producers to more precisely control the number of replacement heifers produced. This

allows producers to generate the desired number of dairy replacements from a smaller proportion of the cow herd while freeing the remainder for other breeding decisions such as for BxD (De Vries et al., 2008). This is reinforced by the annual January 1 cattle reports, in which dairy replacement females have trended downward from 4.8 million head in 2016 to 3.9 million in 2026, whereas the dairy cow herd has gone from 9.3 million to 9.6 million across the same time frame

(United States Department of Agriculture [USDA] National Agricultural Statistics Service [NASS], 2026). The 0.9 million head decrease in replacement females paired with a 0.3 million head increase in dairy herd size further suggests that producer retention and culling decisions have shifted and a portion of cows that historically would have been replaced are now remaining in the herd longer. With the dairy cow herd increasing and the number of replacement females decreasing, there has been growing interest in the demographics of the remaining calf crop and the economic opportunity it represents for dairy producers.

Market analysts have indicated that the remaining calf crop is either marketed as straightbred dairy or Beef-on-Dairy (BxD) feeder calves. A BxD calf is defined as the product of crossbreeding a dairy cow to a beef bull with the purpose of entering the beef supply chain (Berry, 2021). Historically, there has been no data or information on the number of BxD cattle in any USDA market reports. Using data that is currently available (**Figure 1-1**), the annual number of straightbred dairy calves slaughtered has decreased from 1.7 million head in 2015 to 0.22 million head (87% decrease) in 2025 (USDA Agricultural Marketing Service [AMS], 2026). This dramatic decline strongly suggests a fundamental shift in how dairy calf crops are being bred and marketed.

There have also been shifts in the beef supply chain regarding fed cattle with dairy genetics. In 2017, Tyson announced that they would stop buying fed dairy cattle. This changed market supply dynamics and led to dairy producers altering their breeding strategies and opting to produce a greater number of BxD offspring (Schwab et al., 2024). While this change had short-run impacts on the market for dairy genetics in the feeder calf and fed cattle markets, such as a sharp decrease in demand, it spurred investments into genetic selection to optimize BxD production. The long-run result of these changing market dynamics is that BxD offspring now allow dairy cows to add value by producing a more marketable and profitable beef product. Beef was often seen as a byproduct of dairy production, but BxD offspring can now generate more income for dairy producers (Berry, 2021).

While there has been an increasing number of BxD offspring, there has also been progress in how these cattle are valued. It used to be assumed that BxD cattle took longer to reach market weight. However, the rise in BxD crosses led to breeding dairy females with higher quality beef semen that offsets the lower feed efficiency, lower dressing percentage, and smaller ribeye areas associated with straightbred dairy (Dairy Beef Management Guide, n.d.). Thus, BxD cattle can produce a more consistent and slightly higher quality graded product compared to either traditional beef or straightbred dairy. This can lead to premiums for BxD cattle placed in feedyards in comparison to the straightbred dairy cattle. Thus, BxD cattle provide an opportunity to potentially increase revenue for dairy producers.

The absence of formal USDA reporting for BxD cattle creates a price transparency issue, particularly as the number of BxD cattle in the beef supply increases, an issue exacerbated during times of tight cattle supplies. Price transparency issues have been well documented in other agricultural commodity markets. Agricultural economists have long recognized that when buyers

have access to market information that sellers do not, it can lead to systematic underpricing of commodities and suboptimal producer decision-making (Akerlof, 1970). In the cattle industry specifically, the introduction of mandatory price reporting under the Livestock Mandatory Reporting (LMR) Act of 1999 was motivated precisely by this information asymmetry concern, with producers receiving less than market value for their cattle because they lacked access to the transaction price information available to packers and order buyers (USDA AMS, n.d.). This study provides the first systematic quantification of BxD market presence, a necessary precursor to the development of formal reporting infrastructure that would allow the market to function with full price transparency. The objective of this study was to estimate the annual number of BxD cattle in the U.S. beef supply chain from 2016 to 2025 and to evaluate whether statistically significant correlations exist between BxD headcount and national USDA data on fed cattle weights, prices, quality grades, and yield grades.

Literature Review

Most of the previous literature on BxD has either been focused outside the U.S. or is outdated. The literature on the influence of sire breed on the growth and carcass metrics of BxD offspring is outdated, such that its relevance to current genetics may be limited (Pahnish et al., 1969; Southgate et al., 1982, 1988). Literature based on studies outside the U.S. can be informative but does not translate directly to the current U.S. beef production system due to genetic and management changes over time. Additionally, different lineages and selection parameters decrease the application of these studies to the U.S., particularly the prevalence of Friesian-Jersey crossbred dairy cattle in New Zealand and dual-purpose Brown Swiss cattle in European systems, both of which differ fundamentally from the Holstein-dominant U.S. dairy herd (Basiel et al., 2024; Williamson et al., 2022; Lindtke et al., 2024). Despite these limitations,

lessons from international BxD markets are instructive. In New Zealand, where BxD cattle represent approximately two-thirds of the national beef killed, researchers have documented that dam breed composition significantly influences BxD carcass outcomes, and that the value of BxD production is highly sensitive to genetic distance between the dairy dam and beef sire breeds (Williamson et al., 2022). This finding has direct relevance to the U.S. context where the Holstein dam's extreme selection for milk production creates a large genetic distance from beef breeds, suggesting the improvement potential from BxD crossbreeding may be even greater in the U.S. than in countries with dual-purpose breeds.

There are multiple studies from the U.S. that provide further insight into the feedlot performance and carcass characteristics of BxD offspring and how they differ from traditional beef and straightbred dairy (Schwab et al., 2024). In a study comparing BxD steers to straightbred dairy steers, the BxD steers were more feed efficient and produced carcasses with more desirable carcass yields, resulting in greater feeder calf value when compared with Holstein steers (Pimentel-Concepción et al., 2024). These performance advantages have direct economic implications. Research in other livestock sectors demonstrates that feed efficiency improvements of the magnitude observed in BxD cattle translate to meaningful reductions in cost of gain at the feedyard level, typically in the range of $15 to $30 per head, making BxD cattle more profitable for feedyard operators commanding higher prices as a result (Basiel & Felix, 2022).

Similarly, these carcass characteristics are imperative when trying to compare straightbred dairy and BxD animals from a quality and yield grade standpoint. The quality grades of BxD carcasses and the opportunity for these crossbreds to capture premiums are a main point of interest for the BxD market participants (Schwab et al., 2024). However, these types of premiums are examples of market information not provided to producers via USDA reports, a

gap that is particularly consequential given the documented relationship between market information access and producer pricing outcomes. Research in the poultry industry, which underwent mandatory production reporting under the Packers and Stockyards Act, demonstrated that the introduction of price transparency mechanisms increased average producer returns (MacDonald, 2012). While the cattle and broiler industries differ structurally, this finding illustrates a broader principle that price transparency improvements benefit producers, which is a principle directly applicable to the gaps mentioned in this study.

Foraker et al. (2024) analyzed how the carcass characteristics differed between straightbred dairy cattle, both low- and high-yielding BxD cattle, and traditional beef steers. According to the USDA AMS, yield grades range from 1 to 5, where yield grade 1 represents a leaner carcass with the highest proportion of retail cuts and 5 represents the lowest percentage of retail cuts and higher amounts of external fat cover (USDA, 1997). The post hoc sample was comprised of 99 carcasses made up of the three cattle types broken up into the four groups (subsample segregates high- and low-yield BxD cattle). A multiple linear regression assessed the relationship between cattle type and carcass traits. Results indicated that high-yielding BxD cattle and traditional beef cattle produce similar subprimal yields and cutout values statistically comparable to each other. This demonstrates that BxD can more effectively compete with traditional beef carcasses than straightbred dairy carcasses. Understanding these carcass traits aids in determining the value of these animals at slaughter, allowing dairy producers to make decisions regarding the use of BxD on their operations.

The broader agricultural economics literature further reinforces why quantifying BxD market presence matters beyond the individual farm level. Research on the adoption of new livestock production practices consistently shows that producer adoption rates accelerate

significantly once reliable market price data becomes available, because price signals reduce the perceived risk of adoption and allow producers to more accurately forecast returns (Huffman & Evenson, 2006). The rapid growth of BxD production documented in this study suggests that producer adoption is already well advanced. However, without formal price reporting, producers are making management decisions based on incomplete information. This study contributes to the development of formal BxD reporting infrastructure that would allow the market to function with full price transparency.

Research Design and Strategy

Beef-on-Dairy (BxD) Estimation

Quantitative data compiled from the Monthly and Quarterly Cattle on Feed (COF) reports, aggregated weekly marketing reports matching COF reports, and annual January 1 Cattle Inventory reports were used to estimate the total number of BxD calves in the U.S. To estimate the annual number of total BxD calves each year, we first estimated the dairy calf crop and removed the replacements by using a combination of the USDA's January 1 Cattle Inventory report from the year being estimated and the subsequent year's January 1 Inventory report. For example, to estimate the 2025 BxD headcount, we took the 2025 dairy cow inventory and subtracted the 2026 dairy replacement inventory. We then adjusted the calf crop estimate by subtracting the total number of cattle marketed as straightbred dairy that we calculated from the USDA Weekly 5 Market Area Report. This yields our estimate for the maximum number of BxD calves possible each year. Equation 1 explicitly shows the calculations:

$$\text{Max \# Available for BxD in year } t = D_t - DR_{t+1} - ASB_t \quad (1)$$

Where D_t equals the number of U.S. Dairy Cows (January 1 report) in year *t*, DR_{t+1} equals U.S. Dairy Replacements (January 1 report) in year *t+1*, and ASB_t equals Annual Straightbred Dairy Slaughtered (Weekly 5 Area Report) in year *t*.

It is important to note that the annual estimated number of BxD calves is not adjusted for calving rate and death loss. Calving rates for U.S. dairy herds typically range from 85 to 90%, and pre-weaning death loss adds an additional 5 to 8% reduction before calves reach market (Hare et al., 2006; Groenendaal et al., 2004). Given that the estimate does not account for the above-mentioned adjustments, the estimate represents an upper bound on possible BxD placements rather than a confirmed headcount. Additionally, the timing structure of the January 1 cattle inventory report creates a potential for the total number of heifers retained as replacement females to be underestimated. Heifer calves born early in the calendar year may have already been developed, bred, and transitioned to the bred heifer category by January 1 of the following year, thus not appearing in the replacement heifer inventory to adjust our BxD estimate. This further reinforces the characterization of our estimate as an upper bound rather than a confirmed headcount, as it would lead to an overestimate of the possible BxD calves. Finally, this analysis utilizes national USDA data, meaning the results and correlations reflect an aggregate of U.S. market conditions and do not reflect regionally specific market systems.

Estimation Correlation to Reports

With our annual estimate of BxD placements, we calculated Pearson product-moment correlation coefficients to test whether statistically significant relationships exist between our BxD estimate and common USDA fed (5 Area Market Report) and feeder cattle reports (National Feeder Calf Price). Correlation coefficients were calculated using the $= Correl()$ function in Microsoft Excel which calculates the Pearson product-moment correlation coefficient between two arrays

of data. The correlation coefficient *r* measures both the strength and the direction of the linear relationship between two continuous variables, ranging from -1 to +1. Values approaching +1 indicate a strong positive relationship and values approaching -1 indicate a strong negative relationship. Values near zero indicate no linear relationship. This method was selected because it is widely used to measure linear association between continuous variables (Cohen et al., 2003). We estimated these correlations over 9 years, spanning from 2017 to 2025, between the BxD headcount estimate and the following USDA data:

- Live steer weight – from the USDA 5 Area Market Report
- Live steer price – from the USDA 5 Area Market Report
- Dressed steer weight – from the USDA 5 Area Market Report
- Dressed steer price – from the USDA 5 Area Market Report
- Live heifer weight – from the USDA 5 Area Market Report
- Live heifer price – from the USDA 5 Area Market Report
- Quality grade headcounts – Prime, Choice, Select, and Other branded – from USDA AMS carcass grading reports
- Yield grade – Yield Grades 1 through 5 – from USDA AMS carcass grading reports

Following the calculation of each Pearson r coefficient, statistical significance was assessed by converting each correlation to a t-statistic using the formula: $t = \frac{r\sqrt{n-2}}{\sqrt{1-r^2}}$. Where *r* is the Pearson correlation coefficient and n is the number of annual observations (n=9). This t-statistic follows a t-distribution with $n - 2$ degrees of freedom under the null hypothesis that the true population correlation equals zero. Two-tailed p-values were then obtained in Excel using the formula $= T.DIST.2T(ABS(t), 7)$. These two-tailed tests were selected because we did not specify the direction of the expected relationship prior to analysis, allowing us to detect both

positive and negative correlations that achieve statistical significance. With 9 annual observations and 7 degrees of freedom, a correlation coefficient must exceed ±0.666 in absolute value to be significant at the 5% level and must exceed ±0.798 to achieve significance at the 1% level. These critical values reflect the limited statistical power inherent with a sample of 9.

Results

Beef-on-Dairy (BxD) Estimation

Figure 1-2 shows our BxD headcount estimates from 2016 to 2025 compared to the total number of cattle placed into the feedyard each year (placements). Our 2016 estimate for the maximum number of BxD cattle was 2.8 million head. This estimate steadily increased to 5.4 million head in 2025. **Figure 1-3** displays the amount of BxD cattle as a percentage of placements. This number has increased steadily from 13% in 2016 to 26% in 2025 with an average increase of approximately 1.4% per year.

Estimation Correlation to Reports

Table 1-1 presents the Pearson correlation coefficients between our annual BxD headcount estimate and live and dressed steer and heifer weight and prices from 2017 to 2025. All eight correlations were positive and statistically significant at the 5% level or better. Live steer weight, dressed steer weight, and live heifer weight were all significant at the 1% level. This indicates that BxD headcount and average fed cattle weights were positively associated over the study period. Dressed heifer weight was also positive and significant at the 5% level. All four price correlations were positive and significant at the 5% level. When interpreting these results, it is important to recognize the time period from 2017 to 2025 coincides with the tightest U.S. beef cattle supply since 1961, and rising cattle prices over this period reflect multiple supply and demand forces beyond the BxD headcount alone.

Table 1-2 displays the Pearson correlations that were also conducted between the estimated BxD headcount and USDA Quality grade headcounts over the same study period. The number of cattle that graded Prime and our BxD headcount estimate exhibited a strong positive correlation, with significance at the 1% level. This is consistent with the documented tendency of BxD cattle to grade at higher quality levels than straightbred dairy cattle due to improved intramuscular fat deposition from beef genetics (Foraker et al., 2024). The number of cattle grading select exhibited a strong negative correlation with our BxD headcount estimate, significant at the 1% level. This observed relationship suggests that higher numbers of BxD cattle are associated with improvements in the quality grade distribution of the U.S. fed cattle supply. Choice grade cattle and Other branded cattle did not exhibit statistically significant correlations with BxD headcount at the 5% level.

Table 1-3 displays the correlations with our BxD estimate and USDA Yield grade headcounts, also from 2017 to 2025. Yield grade 1 exhibited a strong negative relationship with BxD headcount, significant at the 1% level. Yield grade 1 represents the leanest carcasses with the highest proportion of retail cuts. This suggests a positive relationship with BxD numbers and cattle with more muscle and fat cover being produced. Yield grade 2 exhibited a similar strong negative correlation, significant at the 5% level. Yield grade 3 showed a moderate negative correlation, significant at the 5% level. Yield grade 4 did not achieve statistical significance. Yield grade 5, representing the heaviest and most over-finished carcasses, exhibited a strong positive correlation with BxD headcount, significant at the 1% level. These findings are consistent with BxD cattle producing more external fat than straightbred dairy cattle.

All three correlation tables present a consistent picture, as BxD headcount has increased from an estimated 3.24 million head in 2017 to an estimated 5.44 million head in 2025, the U.S.

fed cattle supply has shifted meaningfully toward heavier carcasses, higher quality grades, and yield grades more consistent with beef genetics. These findings are consistent with the documented carcass advantages of BxD cattle over straightbred dairy and provide empirical validation that the estimated BxD headcount tracks logically with observable changes in national USDA carcass data (Foraker et al., 2024; Pimentel-Concepción et al., 2024; Schwab et al., 2024).

Summary and Implications

This study helps bridge the gap between the anecdotal evidence that hints at the increasing availability of BxD cattle in the beef supply chain and the empirical documentation needed to inform producer and industry decision-making. Prior to this study, producers, market analysts, and industry participants had suggested that BxD cattle were becoming an increasingly significant segment of the U.S. fed cattle supply, yet no systematic quantification of that presence existed in the academic or USDA reporting literature (Berry, 2021; Poock & Beckett, 2022). Our estimates confirm that suspicion empirically, showing BxD placements have grown from approximately 2.8 million head in 2016 to 5.4 million head in 2025, nearly doubling over this period and making up approximately one quarter of the U.S. cattle on feed. It is important to note that feeder cattle with straightbred dairy genetics make up approximately 10% of placements. The fact that market data exists for straightbred dairy animals highlights our need for more BxD market information, considering our BxD headcount estimate suggests BxD cattle currently make up approximately one quarter of placements. This highlights a potential price transparency issue in the current USDA market reports. This price transparency issue has real-world impact. Quaassdorff and Hicks (2023) documented that dairy producers and stakeholders often do not align their sire selection decisions with buyer preferences, a misalignment that can be at least partially attributed to the absence of reliable BxD price benchmarks. This study

provides current, applicable data for the U.S. dairy and beef supply chains that begins to address this gap, offering the first empirically grounded estimates of BxD market presence and its relationship to national carcass quality and yield grade trends. These results provide a foundation contribution that future research and policy efforts can build upon as formal BxD reporting continues to develop.

This study is not without limitations. Most notably, the headcount estimate of BxD cattle in the feedlot represents a derived upper-bound estimate rather than a directly observed count. Because there is no formal USDA required reporting, no ground truth figure exists against which to validate the estimate. The estimate does not adjust for calving rate or death loss, meaning the true number of BxD placements is likely somewhat lower than estimates presented here. Additionally, the correlation analysis was conducted using nine observations spanning from 2017 to 2025, somewhat limiting the power and generalizability of the findings. Furthermore, this study was conducted during a period of historically tight U.S. beef cattle supplies, which may have artificially elevated the market value and feedyard demand for BxD cattle relative to what would be observed during times with a larger supply of cattle. As BxD supply expands and formal reporting infrastructure matures, the relationships identified here should be revisited and refined.

In conclusion, this study helps quantify the impact of BxD in the beef supply chain within the United States. Relevant information applicable to the U.S. can help provide significant improvements to both the dairy and beef supply chains. Up until this study, the number of BxD cattle has not been a focus in previous literature. Knowing the approximate number of BxD cattle aids both the beef and dairy industries by providing producers and industry stakeholders alike with market information that is vital in understanding current market dynamics and providing

stronger market outlooks. This study contributes valuable market information, helping shape a more data-driven approach to analyzing BxD in both the beef and dairy supply chains.

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Appendix

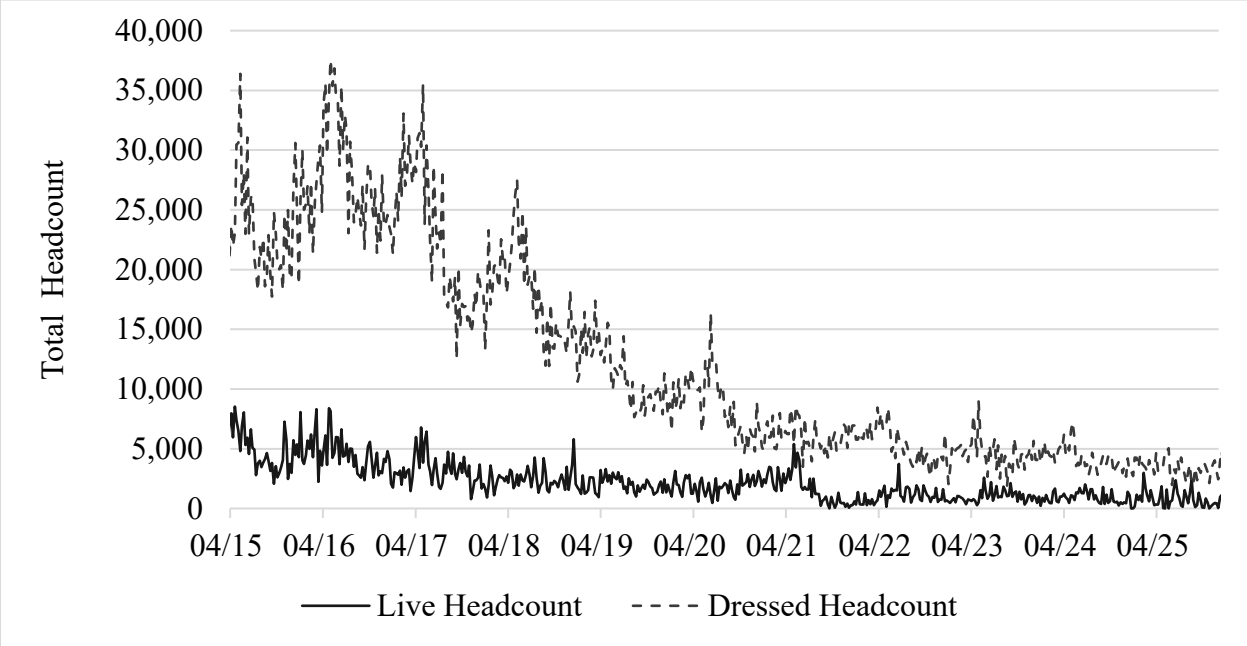


Figure 1-1. Weekly Headcount of Straightbred Dairy Steers and Heifers Marketed as Live and Dressed in the United States, 2015–2025

Note: Data represent the weekly number of straightbred dairy steers and heifers reported in the USDA Agricultural Marketing Service (AMS) 5 Area Weekly Direct Slaughter Cattle Report, separated by marketing method: live (sold on a live-weight basis) and dressed (sold on a carcass-weight basis). Combined live headcounts (solid light gray line) and dressed headcounts (Dark gray dashed line) declined from approximately 35,000 head per week in 2015 to fewer than 5,000 head per week by 2025, representing an approximately 87% decline in annual straightbred dairy slaughter over the period (from 1.7 million head to 0.22 million head). This decline is consistent with dairy producers shifting breeding strategies away from straightbred dairy calves toward Beef-on-Dairy (BxD) production. Weekly variation reflects normal seasonal slaughter patterns and holiday-week reporting gaps.

Source: USDA Agricultural Marketing Service, 5 Area Weekly Direct Slaughter Cattle Report, 2015–2025.

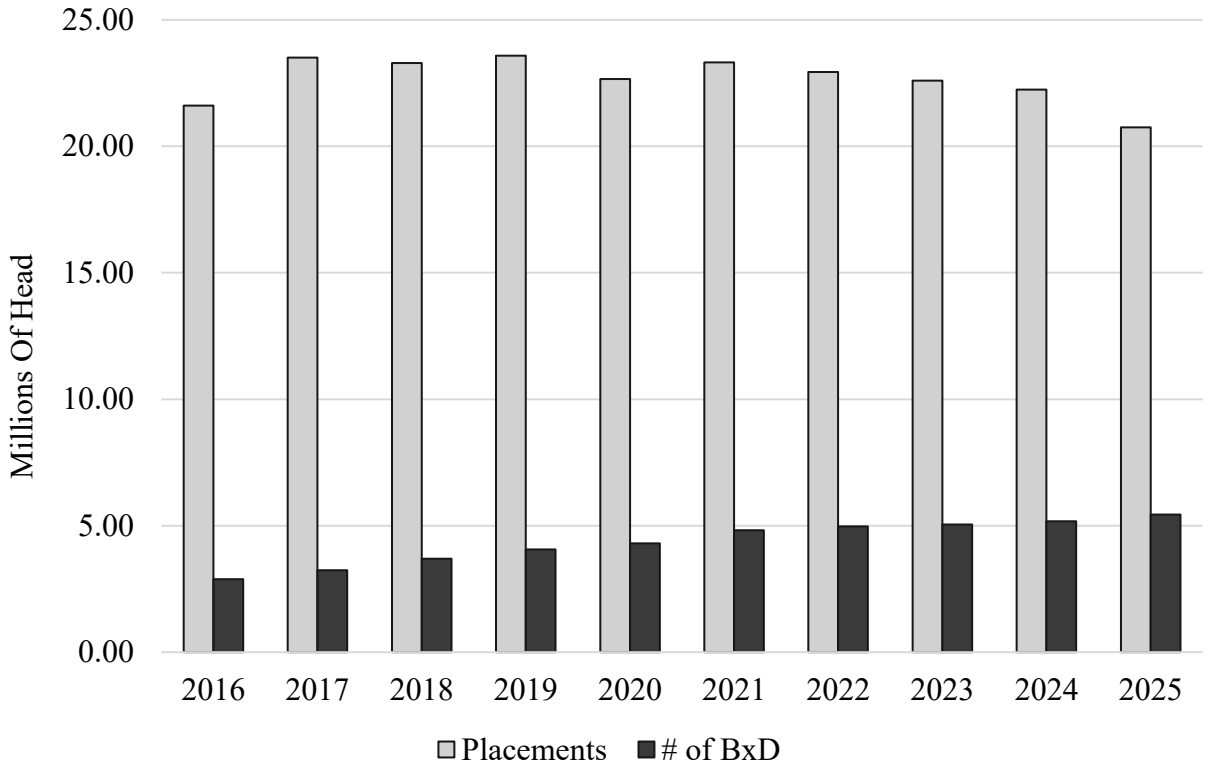


Figure 1-2. Estimated Number of Beef-on-Dairy Cattle Compared to Total Annual Feedlot Placements in the United States, 2016 to 2025

Note: Light gray bars represent total annual cattle placements into U.S. feedlots as reported in the USDA National Agricultural Statistics Service (NASS) Cattle on Feed report. Dark gray bars represent the estimated maximum number of BxD calves available for placement each year, calculated as: dairy cow inventory (January 1 report, year *t*) minus dairy replacement inventory (January 1 report, year *t+1*) minus annual straightbred dairy slaughter (USDA AMS 5 Area Weekly Report, year *t*). The BxD estimate represents an upper bound because it does not adjust for calving rate (typically 85–90%) or pre-weaning death loss (typically 5–8%). BxD estimates

increased from approximately 2.8 million head in 2016 to 5.4 million head in 2025. Total placements ranged from approximately 20 to 23 million head annually over the same period. Values are reported in millions of head.

Source: USDA NASS, Cattle on Feed Report, 2016–2025; USDA NASS, January 1 Cattle Inventory Report, 2016–2026; USDA AMS, 5 Area Weekly Direct Slaughter Cattle Report, 2016–2025. BxD estimates are authors' calculations.

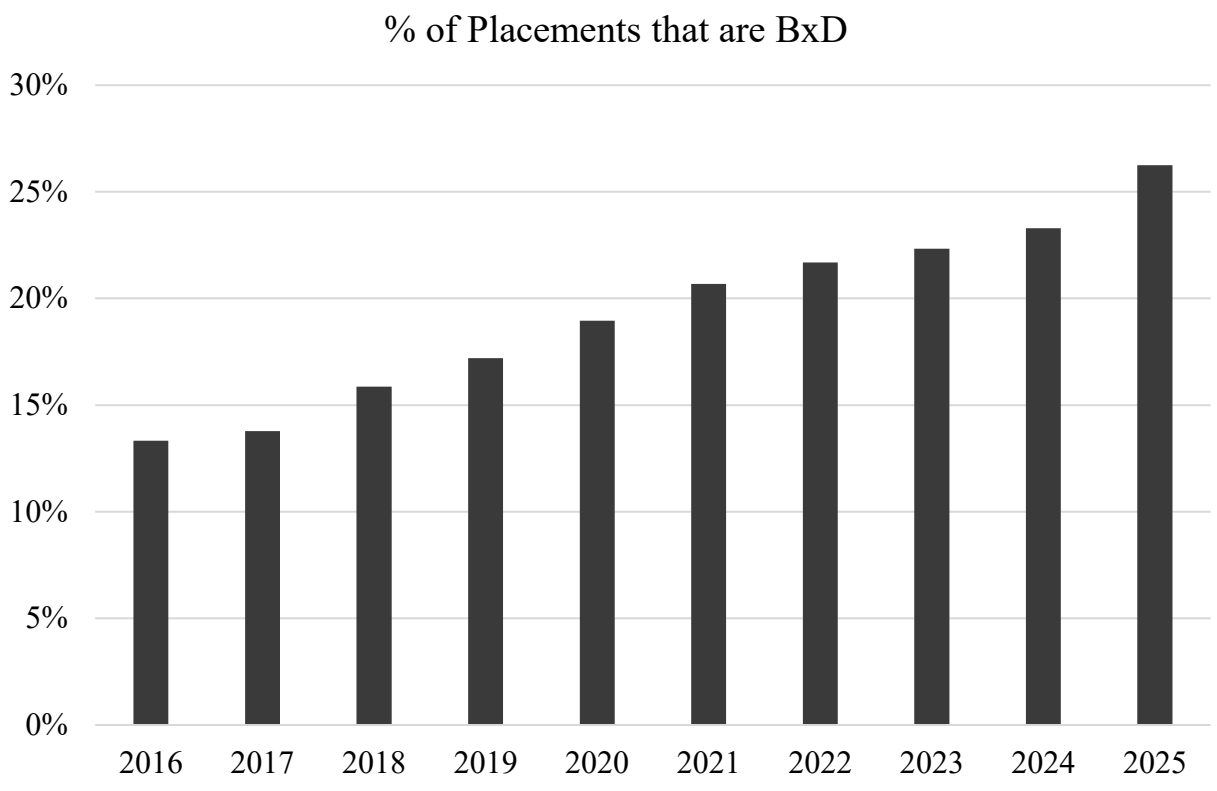


Figure 1-3. Estimated Beef-on-Dairy Cattle as a Percentage of Total Annual U.S. Feedlot Placements, 2016-2025

Note: Each bar represents the estimated maximum number of BxD calves divided by total annual feedlot placements from the USDA NASS Cattle on Feed report for that year. The BxD share of placements increased steadily from approximately 13% in 2016 to 26% in 2025, with an average increase of 1.4% per year. Because the BxD headcount estimate is an upper bound (not adjusted for calving rate or death loss), the true percentage of placements that are BxD is likely somewhat lower than displayed.

Table 1-1. Pearson Correlations between Estimated Annual Beef-on-Dairy (BxD) Headcount and Average Live and Dressed Steer and Heifer Weights and Prices, 2017-2025

	BxD	**Live Steers**		**Dressed Steers**		**Live Heifers**		**Dressed Heifers**	
Year	Headcount	Weight	Price	Weight	Price	Weight	Price	Weight	Price
2017	3239703	1409.0	121.74	907.2	194.27	1275.4	121.79	830.6	192.57
2018	3695863	1426.4	116.68	915.9	184.73	1281.2	117.51	832.0	186.04
2019	4058416	1426.3	117.59	913.7	187.35	1284.3	117.29	820.1	187.70
2020	4296389	1464.7	108.19	944.2	172.27	1310.0	108.27	843.4	173.29
2021	4824271	1471.0	123.17	951.9	193.68	1315.0	122.63	848.4	193.87
2022	4975405	1469.2	144.52	949.6	229.74	1320.7	143.80	849.9	229.96
2023	5046508	1459.2	176.14	943.3	277.95	1315.4	175.07	836.8	277.45
2024	5178194	1491.5	187.25	960.7	295.86	1332.9	186.38	853.7	295.69
2025	5444700	1522.0	224.37	990.0	353.83	1356.0	223.93	871.0	353.93
r-value	—	0.917***	0.769**	0.911***	0.765**	0.939***	0.764**	0.778**	0.769**
p-value	—	0.001	0.015	0.001	0.016	<0.001	0.016	0.013	0.015

Note: ***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively. Each column reports the annual average weight (pounds) or price (dollars per hundredweight, $/cwt) for the indicated cattle class from the USDA AMS 5 Area Weekly Direct Slaughter Cattle Report. The BxD headcount column reports the estimated maximum number of BxD calves for each year. Pearson product-moment correlation coefficients (r) were calculated in Microsoft Excel using the =CORREL() function. Statistical significance was assessed via a two-tailed t-test with $n - 2 = 7$ degrees of freedom under the null hypothesis that the true population correlation equals zero. With $n = 9$ annual observations, correlations must exceed ±0.666 in absolute value to achieve significance at the 5% level and ±0.798 to achieve significance at the 1% level.

Source: USDA AMS, 5 Area Weekly Direct Slaughter Cattle Report, 2017–2025; BxD headcount estimates are authors' calculations.

Table 1-2. Pearson Correlation Coefficients between Estimated Annual Beef-on-Dairy (BxD) Headcount and USDA Quality Grade Headcounts, 2017–2025

	BxD	**Quality Grade (Headcount)**			
Year	Headcount	Prime	Choice	Select	Other
2017	3239703	1506077	17962653	4473154	47316
2018	3695863	2023371	18145264	4427425	59086
2019	4058416	2194124	18138934	4351286	60637
2020	4296389	2496668	17850107	3433195	65835
2021	4824271	2544931	18296039	3623618	74062
2022	4975405	2274157	18657270	3810473	72382
2023	5046508	2245831	17729448	3564728	64683
2024	5178194	2499301	17566253	3306306	56338
2025	5444700	2701567	16596249	2847503	61843
r-value	—	0.841***	-0.413	-0.876***	0.553
p-value	—	0.004	0.269	0.002	0.123

Note: ***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively. Quality grade columns report the total number of federally inspected cattle grading at each level (Prime, Choice, Select, and Other Branded) annually, as published in USDA AMS carcass grading summary reports. The BxD headcount column reports the estimated maximum number of BxD calves for each year. Pearson product-moment correlation coefficients (r) were calculated in Microsoft Excel. Statistical significance was assessed via a two-tailed t-test with $n - 2 = 7$ degrees of freedom. With $n = 9$ observations, correlations must exceed ±0.666 in absolute value to achieve significance at the 5% level and ±0.798 for the 1% level. Choice and Other branded do not achieve statistical significance at the 5% level given the available sample size.

Source: USDA AMS, Annual Carcass Grading Summary Reports, 2017–2025; BxD headcount estimates are authors' calculations.

Table 1-3. Pearson Correlation Coefficients between Estimated Annual Beef-on-Dairy (BxD) Headcount and USDA Yield Grade Headcounts, 2017–2025

	BxD	**Yield Grade (Headcount)**				
Year	Headcount	#1	#2	#3	#4	#5
2017	3239703	439901	2370929	3461318	706997	105573
2018	3695863	411129	2538842	3441759	759559	140284
2019	4058416	376542	2428389	3469414	808615	125861
2020	4296389	259262	2027257	3404149	881202	162317
2021	4824271	233998	1974529	3350609	928976	189499
2022	4975405	223883	1915230	3396651	916093	199920
2023	5046508	173918	1361699	2741482	748443	155962
2024	5178194	96009	872693	2374150	783809	174579
2025	5444700	61623	744107	2296031	821845	196882
r-value	—	-0.961***	-0.857***	-0.745**	0.441	0.870***
p-value	—	<0.001	0.003	0.021	0.234	0.002

Note: Yield grade columns report the total number of federally inspected cattle grading at each yield grade level (1 through 5) annually, as published in USDA AMS carcass grading summary reports. The BxD headcount column reports the estimated maximum number of BxD calves for each year. Pearson product-moment correlation coefficients (r) were calculated in Microsoft Excel. Statistical significance was assessed via a two-tailed t-test with $n - 2 = 7$ degrees of freedom. With $n = 9$ observations, correlations must exceed ±0.666 in absolute value for 5% significance and ±0.798 for 1% significance. ***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively. Yield Grade 4 (r = 0.441, p = 0.234) does not achieve statistical significance at the 5% level. Yield Grade 3 (r = −0.745, p = 0.021) is significant at the 5% level. All other reported correlations are significant at the 1% level. Correlations measure linear association and do not imply causation.

Source: USDA AMS, Annual Carcass Grading Summary Reports, 2017–2025; BxD headcount estimates are authors' calculations.

Chapter 2: Price Integration and Market Leadership of Beef-on-Dairy Markets

Introduction

In any farm enterprise, economic and production management are critical components of efficiency, sustainability, and profitability. High input costs, volatile milk prices, and rapidly changing consumer demands for milk and other dairy products have created major challenges for United States (U.S.) dairy farms (MacDonald et al., 2020). Today, dairies are attempting to remain profitable by incorporating value-added enterprises such as agri-tourism, cheese-making, and other dairy food items (MacDonald et al., 2020). This has sustained some dairies, but these value-added businesses typically require substantial capital investments in equipment, financial risks, labor needs, and new and specialized management expertise (Eckelkamp et al., 2021).

A potentially lower-cost and less risky way to increase profitability is to add value to calves sold by breeding dairy cows to beef sires, which is commonly referred to as "beef-on-dairy" (McHugh et al., 2011; Berry, 2021; McCabe et al., 2022; Hurst et al., 2023). This is not a new concept for the dairy industry (Beanaman et al., 1962; Wellington, 1971), but until recently, intentionally breeding a portion of dairy females to specific beef bulls was not common in dairy production (Poock & Beckett, 2022).

Supporting evidence is found in semen sales (**Figure 2-1**). Since 2012, U.S. beef semen units sold have increased 483% while dairy semen units sold declined 30% (National Association of Animal Breeders, 2024). The growth in domestic beef semen sales can be primarily attributed to the U.S. dairy industry shifting from using dairy sires to breed dairy females to using beef sires to produce beef-on-dairy (BxD) calves in order to capture higher prices compared to straightbred dairy calves (Basiel & Felix, 2022; Jaborek et al., 2019; Poock & Beckett, 2022).

This recent and rapid growth of BxD production in the U.S. has induced many questions from producers and industry stakeholders. Researchers have explored several critical dimensions of BxD production, including feedlot performance and feed efficiency (Jaborek et al., 2019, 2023; Foraker et al., 2022), beef quality and yield grade differences between BxD and traditional beef carcasses (Basiel et al., 2024; Basiel & Felix, 2022; Foraker et al., 2022), dairy producer motivations and sire selection (Pereira et al., 2022; Felix et al., 2023) and the implications of beef semen use on conception rates (McWhorter et al., 2020). Collectively, this literature establishes that BxD cattle outperform straightbred dairy cattle in feedlot performance and carcass metrics, and that dairy producer motivations are primarily economic in nature.

Historically, BxD market information has been limited due to a lack of reporting. Without reliable data, it can be problematic for producers to make proper management decisions with both the current markets and the future in mind. More specifically, without proper headcount and pricing information of BxD cattle, a possible price transparency issue may arise. For example, a dairy producer selling BxD calves has no standard benchmark price to reference, unlike a traditional beef producer who can reference United States Department of Agriculture's (USDA) Agricultural Marketing Service (AMS) feeder cattle reports to determine if the price offered reflects the current market conditions. This means that as BxD sales rise, the absence of a formal BxD USDA reporting category means that BxD producers are taking part in transactions that do not have the same price transparency infrastructure that exists for every other major cattle class.

Cointegration analysis has long been applied to feeder calf prices (Bessler & Covey, 1991). These prices influence profitability for producers and feeders throughout the beef supply chain. As feeder calves move through each segment in the supply chain, their price provides insight into both current conditions and expectations moving forward. Cointegration allows for

long-run evaluation among price series. The results allow researchers to determine stability within the markets (Engle & Granger, 1987; Johansen, 1991). Thus, providing proper information helps with data-driven management decisions.

Historically, this type of cointegration has not been possible with BxD cattle because market information was not reported. Recently, voluntarily reported BxD numbers from the USDA AMS have become available. This study uses this data to evaluate price integration, market leadership, and forecasting using a vector error-correction model (VECM). The price integration analysis evaluates if the geographically dispersed markets move together in the long run and if the relationships are consistent with the law of one price (Muwanga & Snyder, 1997). Identifying market leaders shows which markets lead price discovery and which markets follow, allowing producers and buyers to make decisions based on price signals (Wright et al., 2021). The VECM framework captures both short-run price dynamics and long-run relationships. This model has historically been applied to the U.S. cattle and feeder calf markets to confirm market efficiency and price transmission (Bessler & Covey, 1991; Coffey, 2025). Utilizing these tools provides the most comprehensive framework available to understand how BxD prices form, transmit, and lead across BxD markets. These studies establish cointegration and price leadership analysis as the standard tools for understanding spatial market structure in U.S. livestock markets, yet no study has applied them to BxD cattle. This study addresses that gap by asking two questions: (1) Are geographically dispersed auction markets integrated in the long run? (2) Among the integrated markets, which locations serve as price leaders?

Literature Review

Profitability for dairy producers is regionally dependent. **Figure 2-2** displays net returns (profits) per cwt to milk production for Southeastern dairy farms (Virginia, North Carolina, South

Carolina, Georgia, Florida, Alabama, Mississippi, Tennessee, Kentucky, Arkansas, Louisiana) compared to the U.S. (USDA Economic Research Service [ERS], 2022). Dairies in this region have higher feed and labor costs due to not being able to capture lower costs from economies of scale (MacDonald et al., 2020). MacDonald et al. (2020) shows that economies of scale (lower costs as output increases) is a driving force in the consolidation of small dairy farmers into fewer and larger dairy farms. The average dairy herd size in the Southeast is 81 head per operation, which is much lower than the national average of 337 (USDA National Agricultural Statistics Service [NASS], 2022). These producers are competing against larger operations with lower production costs. MacDonald et al. (2020) reported that dairies with less than 1,000 head per farm rarely have positive net returns to milk production, which has been a catalyst for small-sized dairies to invest in value-added business opportunities.

As the use of BxD has grown, breeding decisions for dairy producers have become increasingly important, not just for individual farm profitability but for the broader beef supply chain as well. Pahmeyer et al. (2019) applied a theoretical framework using Latin Hypercube sampling to make a single-farm simulation model. With this farm model, they were able to run a simulation of optimal sexed dairy semen, conventional dairy semen, and crossbreeding usage. Their study found using both conventional and sexed beef semen on a dairy farm to be profit maximizing for 21% of all inseminations. This percentage shifts in response to factors such as changes in calf prices, replacement heifer value, milk prices, and conception rates, meaning that as BxD premiums over straightbred dairy cattle continue to grow, the profit-maximizing share of BxD usage on the dairy farm will expand beyond what Pahmeyer et al. identified. This supports that BxD is not a niche or temporary phenomenon. BxD usage is a rational economic response by dairy producers to market incentives. However, without reliable market data, dairy producers

implementing BxD practices on their operation do not have an accurate way to assess whether their BxD calves are capturing all of the premiums the market may offer, reinforcing the need for formal BxD reporting by the USDA.

Empirically, Pereira et al. (2022) employed a cross-sectional study to understand California dairy producers' preferences on using beef semen in their breeding strategies. The cross-sectional design allowed the authors to capture a snapshot of producer decision-making across a diverse range of operation sizes, management styles, and geographic regions within the state. They found that producers used beef semen on their dairy cows primarily because of the extra profit their progeny generated for their operation. These results are intuitive because BxD calves receive meaningfully higher prices compared to straightbred calves at auction, directly increasing revenue per calf crop without requiring substantial changes to existing management infrastructure or overhead. Although these producers are making profit-motivated decisions, they may still be valuing their BxD cattle relative to what an informed and transparent market would support.

Coffey (2025) found that futures prices for feeder cattle, corn, and live cattle are expected to be linked through production relationships in the cattle feeding sector. The study finds a stable, long-run cointegrating relationship between these commodities, which suggests that the fed cattle markets behave as economic theory predicts under efficient conditions. Previously, it has not been possible to run a similar study on BxD cattle because there has been no data. Our study builds on this concept of cointegration in BxD markets.

Beyond inputs, livestock futures markets exhibit interconnected price behavior across commodities. Panagiotou (2025) investigated the relationship between futures prices for feeder cattle, live cattle, and lean hogs. Their study found that these livestock commodities tend to rise

and fall together. Interestingly, there was a stronger relationship during more extreme downturns than during upswings. While Panagiotou (2025) did not examine BxD cattle specifically, these findings highlight the broader market environment within which BxD feeder calf prices operate, where feeder cattle prices are influenced not only by internal market dynamics but also by broader protein markets.

Spatial market integration has also played a key role in the analysis of the U.S. beef supply chain because transportation costs, regional supply patterns, and marketing channels all impact price dynamics (Faminow & Benson, 1990; Goodwin & Schroeder, 1991). Muwanga and Snyder (1997) used cointegration to determine that most cattle markets within the U.S. were integrated, meaning prices in one market are connected to prices in another market, though the degree of adherence to the law of one price varied by class of cattle as well as region. These findings highlight the need for testing cointegration not only between inputs and outputs within the supply chain but also between geographically separate markets, a gap that particularly exists in regard to BxD, where there has not been spatial price analysis previously conducted despite the rise in BxD production. If traditional beef cattle markets exhibit varying degrees of price integration across regions and cattle classes, it is reasonable to expect that BxD markets may exhibit similar variation, making spatial cointegration analysis not just relevant but essential to better understand BxD price formation and transmission across the U.S.

Price discovery research complements cointegration analysis by identifying which markets lead price adjustment. This is relevant because knowing the source of new price information that other markets follow provides vital information about where the market is headed. Wright et al. (2021) found that futures markets for both feeder and fed cattle serve as dominant price discovery centers in relation to cash markets.

The studies above highlight the opportunity for dairy operations to increase profitability with BxD production. However, without market data, risk management, and long-term planning in relation to BxD is not possible. Other studies have found contrasting results when it comes to challenges for dairy producers when producing BxD calves. Halfman and Sterry (2019) surveyed dairy producers in the Midwest and found that semen cost was key in decision-making. In contrast, Quaassdorff and Hicks (2023) surveyed New York dairy producers and showed that conception rate and calving ease were the top two most key factors impacting decisions, followed by semen cost. Furthermore, Quaassdorff and Hicks (2023) showed that the frame score of the beef sire and carcass EPDs were the least important factors in decisions.

Research Design and Strategy

For this study, we utilized time-series data to investigate price leadership dynamics among BxD markets. All data preparation, estimation, and testing were conducted in Stata. Auction price data reported by AMS, from April 2024 through March 2026, was used to identify market leaders and followers. Identifying market leaders and followers tells dairy producers, feedyard operators, and other industry stakeholders exactly where BxD prices originate and how they transmit across the U.S., allowing for a data-driven foundation for marketing, management, and other decisions for the first time in the BxD realm. A Vector Error-Correction Model (VECM) was utilized because of its ability to analyze price relationships among multiple non-stationary, cointegrated time series, capturing long-run equilibrium relationships as well as short-run adjustments among various market locations (Johansen, 1991; Engle & Granger, 1987). This study uses secondary data and is observational in design. Our analysis exploits natural variation in the weekly auction data across different geographical markets over a period of two years. This design is consistent

with previous literature on spatial market integration (González-Rivera & Helfand, 2001; Faminow & Benson, 1990).

Data

National transaction-level auction price data was obtained from USDA AMS, compiled from mandatory price reports submitted by federally licensed livestock auction markets under the Livestock Mandatory Reporting (LMR) Act. The raw dataset contained 82 variables covering information such as individual lot characteristics, market identifiers, head counts, reported prices, and more. The dataset was filtered to retain only BxD steers and BxD heifers (this BxD information was voluntarily reported). This yielded 9,941 observations across the dataset, including 4,031 BxD heifers (40.55% of the sample) and 5,910 BxD steers (59.45% of the sample). This data was selected because it represents the majority of BxD cattle entering the beef supply chain and was the most consistently reported.

We then collapsed the transaction-level observations into weekly volume-weighted average prices at the market level using head count as the weighting variable. Volume-weighting was employed rather than a simple average to ensure both larger and smaller lots contribute proportionally to the weekly price signal, aiming to minimize impact from any outliers, thus capturing more meaningful price signals while reducing noise from any individual lot-level variation. This aggregation produced 2,528 weekly market-level observations across all reporting markets.

To ensure sufficient time series length for cointegration analysis, markets were required to have a minimum of 50 weekly price observations. The reason for this selection was to exclude markets with incomplete price records that could negatively impact the reliability of the time series estimation. This was not a statistical requirement but instead used as a practical screening

criterion consistent with applied time series practice. This yielded an initial sample of 19 markets spanning 9 states (New Mexico, Texas, Pennsylvania, New York, Indiana, Illinois, South Dakota, Iowa, and Kentucky), representing geographically diverse markets within the U.S.

Unit Root Testing

Prior to cointegration testing, the Augmented Dickey-Fuller (ADF) test was used to confirm that all price series were integrated of order one, by verifying non-stationarity in levels and stationarity in first differences, as required by the VECM framework. One market in Shipshewana, Indiana was excluded from the sample because its price series failed to confirm integration of order one via the ADF test. Including this series in a VECM would violate the theoretical assumptions of the cointegrating framework and produce invalid estimates. This resulted in a final sample of 18 markets. After reshaping the data and applying linear interpolation with extrapolation to address missing weekly observations, the dataset spans 108 weekly observations starting in April 2024 through March 2026. After accounting for the lag structure, 104 usable weekly observations were used, a length of time sufficient for VECM and consistent with the overlapping price coverage across the 18 markets. While a longer time series would be preferable for detecting structural breaks and assessing the stability of price leader relationships over time, the sample size of 104 observations is sufficient to support the VECM framework used in this study.

Johansen Cointegration Test

Using the remaining 18 markets, the Johansen trace test was used to determine the number of cointegrating relationships. The Johansen framework was used because of its ability to identify multiple cointegrating vectors in a system of more than two variables (Johansen, 1991). The trace test sequentially tests the null hypothesis that the number of cointegrating vectors is equal

to rank r, beginning at r=0 (meaning zero relationships) and increasing until the null hypothesis fails to be rejected. The cointegrating rank identified by the Johansen trace test was then imposed directly on the VECM specification.

Vector Error Correction Model

The VECM was then estimated with the cointegrating rank and lag structure identified previously, incorporating the 18 markets as endogenous variables. The VECM captures both how quickly each market returns to equilibrium following a price shock in the long run and the influence of lagged price changes on current prices (short-run price dynamics). The VECM was estimated by using a system of 18 simultaneous equations (one for each market), each taking the general form shown in equation 2.

$$\Delta P_{i,t} = \mu_i + \sum_{r=1}^{10} \alpha_{i,r} \widehat{\varepsilon}_{r,t-1} + \sum_{j=1}^{18} \sum_{l=1}^{3} \beta_{i,j,l} \Delta P_{j,t-l} + u_{i,t} \quad (2)$$

Where:

- $\Delta P_{i,t}$ = first difference of the weekly volume-weighted average price at market *i* in week *t*
- μ_i = market-specific constant term
- $\alpha_{i,r}$ = error correction coefficient for market *i* on cointegrating vector *r* — measures how strongly market *i* responds to deviations from the long-run equilibrium relationship *r*
- $\hat{\varepsilon}_{r,t-1}$ = lagged residual from cointegrating vector *r* — the deviation from long-run equilibrium in the prior week
- $\beta_{i,j,l}$ = short-run dynamic coefficient measuring the effect of lagged price changes at market *j* on current price changes at market *i*
- $\Delta P_{j,t-l}$ = lagged first difference of price at market *j* at lag *l*
- $u_{i,t}$ = white noise error term

Model stability was tested using the eigenvalue condition, confirming that the model

imposed exactly the expected number of unit moduli and that all remaining eigenvalues had modulus strictly less than one, confirming the system is dynamically stable and that price deviations are temporary rather than permanent. The white noise assumption for residuals was assessed using the Portmanteau Q-test at four lags, confirming no evidence of residual autocorrelation and that the lag structure was appropriately specified.

Weak Exogeneity Tests

Finally, price leadership was formally identified using weak exogeneity tests. This was done by testing the null hypothesis that all error correction coefficients (α) for a given market are jointly equal to zero. The error correction coefficients measure the speed and direction at which each market adjusts toward long-run equilibrium following a price deviation. A market whose coefficients are jointly zero does not respond to disequilibrium at all, meaning it sets prices that other markets adjust to rather than adjusting itself. Thus, a market that fails to reject this null hypothesis is classified as a price leader. Conversely, a market that rejects this null hypothesis is a price follower because it is actively adjusting its price in response to deviations from long-run equilibrium, correcting back toward the price set by price leaders. Markets that have a larger chi-square value adjust more rapidly to price shocks. This approach to identifying price leadership is consistent with Johansen (1992) and has been widely applied in prior agricultural market integration studies (Bessler & Covey, 1991; Asche et al., 2004), providing a methodologically rigorous and theoretically grounded framework for price leadership identification which is directly applicable to the emerging BxD cattle markets analyzed in this study.

Results

Unit Root Testing

The 19 markets represented 9 states (New Mexico, Texas, Pennsylvania, New York, Indiana, Illinois, South Dakota, Iowa, and Kentucky). These markets were selected because they met all selection criteria, ensuring reliability for cointegration analysis. Each price series was tested in levels to confirm non-stationarity, a necessary precondition for cointegration analysis. All 19 series failed to reject the null hypothesis of a unit root in levels, confirming that all price series were non-stationary and trended over time without returning to a fixed mean. ADF tests were then conducted in first differences to confirm that one round of differencing was sufficient to produce a stationary series. 18 of the 19 markets rejected the null hypothesis of a unit root in first differences at the 5% significance level. The sole exception was the market in Shipshewana, IN, which failed to reject the null hypothesis, indicating its price series could not be confirmed as stationary after one difference. Thus, Shipshewana, IN was excluded from this analysis, resulting in a final sample of 18 markets. **Table 2-1** shows the market locations and the first-difference ADF results for the original 19 markets, covering 9 states.

Johansen Cointegration Test

Results of the Johansen Cointegration Tests are presented in **Table 2-2**. There were 10 cointegrating relationships identified among the 18 markets. These findings suggest strong long-run price integration. Consider an example where 18 markets act completely independently, with no economic connection; there would be zero cointegrating relationships. Conversely, in an example with 18 perfectly integrated markets, there would be one single national price and 17 cointegrating relationships. Our study resulted in 10 cointegration vectors, falling in between the two extreme examples previously mentioned. In other words, the 18 markets share 10 common

long-run equilibrium relationships, and there are 8 common stochastic trends driving the system. When prices at any given market deviate from underlying forces such as regional supply and demand, transportation cost differentials, and cattle availability, the cointegrating relationships pull prices back toward long-run equilibrium. This process is formally captured by the error correction mechanism in the VECM. These findings suggest strong long-run price integration across geographically dispersed U.S. BxD auction markets, consistent with the law of one price operating at a regional level as opposed to purely the local level.

Vector Error Correction Model

Our VECM was estimated with a cointegrating rank of 10 and 3 lags and incorporated all 18 markets as endogenous variables over all 104 observations from April 2024 to March 2026. Each equation had 65 parameters. **Table 2-3** displays the model fit statistics for the VECM system, while **Table 2-4** displays equation-level results. All 18 equations were statistically significant ($p<0.05$), and R^2 values ranged from 0.718 to 0.981. Thus, the VECM explains between 72% and 98% of the short-run weekly price variation.

It is important to acknowledge the potential limitation of the model fit statistics. There are 104 observations and 65 parameters per equation, exceeding the common recommended ratio of observations to parameters of 10:1 (Greene, 2018). This raises the possibility that the high R^2 observed across equations may partly reflect overfitting rather than genuine explanatory power. However, the VECM is estimated as a system and imposes cross-equation restrictions that reduce effective model complexity relative to an unrestricted vector autoregression (VAR) estimation. Additionally, the main objective of this study is to use the weak exogeneity tests, which test joint restrictions on the error correction coefficients (α) and are less sensitive to individual coefficient overfitting than equation R^2 values. Lastly, the model diagnostics (eigenvalue stability and

Portmanteau Q-test) discussed in the next section confirm the model is correctly specified and that the residuals are well-behaved, which would not happen in a severely over-parametrized model.

The stability of the VECM was formally confirmed via the eigenvalue condition. After estimating the VECM, the model's dynamic properties can be summarized by a set of mathematical values called eigenvalues that describe how the system responds to price shocks over time. An eigenvalue with an absolute value greater than 1 means price shocks grow larger over time rather than dissipating (prices drift farther apart rather than returning to equilibrium). An eigenvalue of exactly 1 is a unit modulus, which represents a unit root, or a permanent stochastic trend in the system. An eigenvalue less than 1 indicates stability within the markets. There were 18 variables and 10 cointegrating vectors; thus, 8 unit moduli (18 variables minus 10 cointegrating vectors). All the remaining eigenvalues had modulus strictly less than 1 (range: 0.16 to 0.98). With this information, we were able to confirm the model was correctly specified and dynamically stable.

After estimating a time series model, it is essential to verify that the model has adequately captured all systematic patterns within the data, leaving only random noise in the residuals. A residual is the difference between what the model predicted and what actually occurred each week. If this week's prediction error is correlated with last week's prediction error, the model has failed to capture something important, and its estimates cannot be fully trusted. The Portmanteau Q-test at 4 lags was used to assess if any residuals exhibit autocorrelation. The null hypothesis of the test is that residuals are white noise (no autocorrelation, no systematic pattern, and constant variance). Failing to reject this null hypothesis indicates that the model has successfully extracted all predictable structure from the data. Results indicated no evidence of residual autocorrelation

across equations, confirming that the model's error terms are white noise. This result validates both that the 3-lag structure was appropriately specified, capturing relevant short-run price dynamics; and that the VECM is correctly specified and did not systematically miss any predictable price patterns. Had autocorrelation been detected, it would have required additional lags or structural modifications before the weak exogeneity results could be interpreted with confidence.

Weak Exogeneity Tests

To identify any price leadership, weak exogeneity tests were run. **Table 2-5** displays these results. Three of the 18 markets were identified as price leaders at or near the 5% significance level. MKT_2046 (Greenville, IL) was the strongest price leader, followed by MKT_2011 (Albany, NY). Additionally, MKT_1784 (Portales, NM) was a borderline price leader. This market had a p-value equal to 0.082, meaning the test fails to reject the null hypothesis of weak exogeneity at the 5% level, and the market is thus classified as a price leader. However, at the 10% level, a p-value of 0.082 would reject the null hypothesis and thus would be reclassified as a price follower. The remaining 15 markets all rejected the null hypothesis at the 5% level, making them price followers. Additionally, markets MKT_2167 (Des Moines, IA), MKT_1908 (New Holland, PA), MKT_2528 (Kalona, IA), and MKT_1953 (Dalhart, TX) all exhibited the most rapid adjustments to price shocks. This suggests they are extremely sensitive to signals from price-leading markets.

Conclusion

This study provides the first empirical analysis of spatial price integration and price leadership dynamics in the BxD markets. Using weekly auction prices from 18 USDA AMS market reports over a two-year period, we estimated a VECM to evaluate long-run equilibrium relationships,

price adjustments in the short-run, and market leadership. Prior to this study, no empirical framework existed to describe how BxD prices form, transmit, or lead across U.S. auction markets, despite BxD cattle making up approximately one quarter of the cattle placed into the feedyard each year. This study addresses that gap directly and provides the first data-driven foundation for understanding BxD market structure.

Our analysis identified 10 cointegrating relationships out of 18 markets. This suggests that these markets are driven by 8 common stochastic trends. The VECM explained between 72% and 98% of weekly price variation across all 18 markets, all of which were statistically significant. The weak exogeneity tests identified three price leaders, MKT_2046 (Greenville, IL), MKT_2011 (Albany, NY), and MKT_1784 (Portales, NM) (at the borderline level).

The finding of 10 cointegrating relationships among 18 markets is consistent with previous research on spatial integration done on U.S. cattle markets. Muwanga and Snyder (1997) found that most feeder cattle markets in the U.S. were integrated, with the degree of adherence to the law of one price varying by cattle class and region. Our results suggest that BxD markets, despite being a newly reported cattle class without any formal USDA reporting requirements, have already developed a level of spatial integration comparable to what has been documented in more established cattle market categories. Bessler and Covey (1991) required decades of data to establish cointegration among traditional cattle prices, yet BxD markets exhibit statistically significant long-run relationships within a much shorter window. This likely reflects the fact that BxD calves are entering the same supply chain as traditional beef and straightbred dairy cattle, meaning that similar economic forces are acting on BxD markets in the same way as traditional feeder cattle markets (Faminow & Benson, 1990; Goodwin & Schroeder, 1991).

The identification of Greenville, Illinois, Albany, New York, and Portales, New Mexico adds a new dimension to price discovery literature. Wright et al. (2021) found that futures markets serve as dominant price discovery centers for both feeder and fed cattle relative to cash markets. Our study operates entirely within the cash auction market because no BxD futures contract currently exists. This is relevant because the emergence of identifiable price leadership suggests even without a centralized price discovery mechanism, certain physical auction markets have assumed a price-setting role for BxD cattle nationally. This finding has practical significance in light of producer decision-making literature. Quaassdorff and Hicks (2023) documented that dairy producers often do not align sire selection decisions with downstream buyer preferences, which can be explained in part by an absence of reliable BxD price benchmarks. Pereira et al. (2022) similarly found that while dairy producers are primarily motivated by profit when using beef semen, they lack market information needed to evaluate whether the prices they receive fully reflect the value of their BxD calves. The price leadership structure identified in this study begins to address that gap. Producers in follower markets can now reference prices at leader markets to use as indicators of broader BxD market direction, providing the type of benchmark that Quaassdorff and Hicks (2023) and Pereira et al. (2022) identified as missing.

Identifying price leadership in BxD markets is important for numerous reasons. First, it confirms that BxD cattle, despite having no formally required reporting category, have developed a functioning price discovery structure consistent with the law of one price operating at a regional level. Additionally, finding dominant price leadership has direct practical implications. Price shocks seen at a market-leading location do not simply reflect changes in local supply and demand; they also influence BxD prices throughout the system at follower markets. This means

that, as a price shock occurs at a market-leading location, it will ultimately be felt by producers and buyers in markets thousands of miles away.

These findings carry direct and actionable implications for every segment of the BxD supply chain. Dairy producers benefit the most from these results, allowing them, for the first time, to see how prices originate and transmit across markets. Producers in follower markets now have evidence that gives them a forward-looking benchmark to evaluate whether the price they are being offered reflects current national BxD market conditions. Producers receiving prices substantially below what the market leaders are reporting should consider whether their local market fully reflects national price signals and whether timing or location of sales could capture better returns.

Additionally, feedyard operators, order buyers, and packers benefit from understanding the price transmission structure documented in this study. Buyers sourcing BxD calves nationally can use this information as indicators of broader market direction, providing a competitive information advantage in procurement. For industry organizations and USDA policymakers, the most important implication is that these findings provide the first empirical justification for creating a formal BxD commodity class under the LMR Act, demonstrating that BxD markets are sufficiently mature, integrated, and economically significant to warrant the same price transparency infrastructure that exists for every other segment of the U.S. cattle industry.

Admittedly, this study is not without limitations. Although the two-year sample period is sufficient for the analysis run, formal BxD reporting is still very new. As more data becomes available, market relationships may evolve and shift, particularly as new auction markets accumulate sufficient price history and as herd rebuilding occurs following the tightest beef supply since 1961, which alters the supply dynamics that partially shape the price relationships

documented in this study. Additionally, as the time series lengthens, re-estimation of the VECM will allow researchers to assess whether the identified relationships are stable or if structural breaks emerge as the BxD market matures. The application of impulse response functions and forecast error variance decomposition in future research will further quantify the speed and magnitude of price transmission from leader to follower markets, providing even more information for producers and stakeholders.

Despite these limitations, the U.S. BxD cattle market exhibits meaningful long-run price integration and an identifiable price leadership structure that has direct implications for producers, buyers, packers, and policy makers alike. These results fill a critical gap in the literature by providing empirical evidence of how BxD prices interact across markets. This research provides a foundational framework for much-needed ongoing monitoring of BxD market efficiency and impact on both the beef and dairy supply chains.

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Appendix

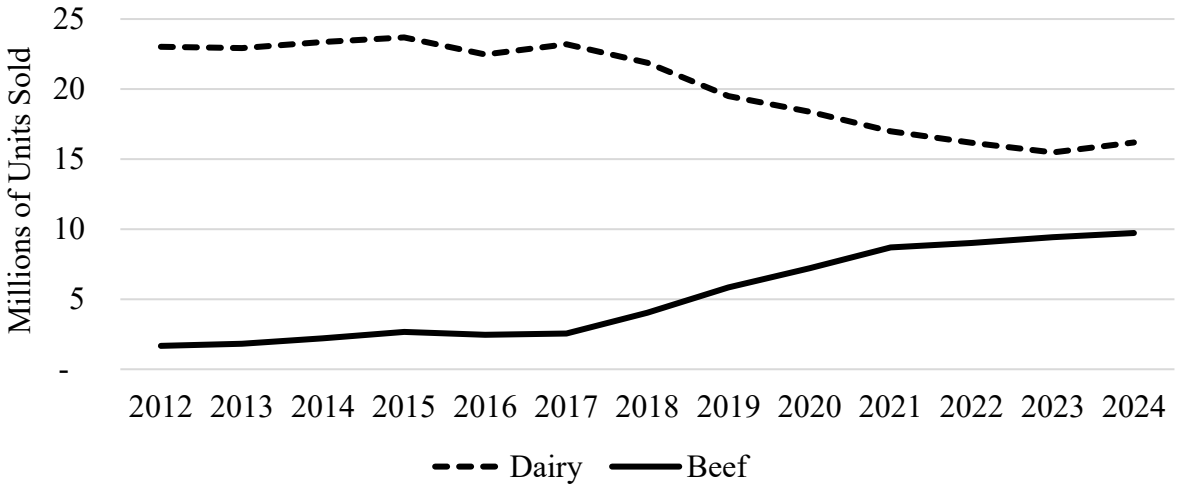


Figure 2-1. Annual Domestic Beef and Dairy Semen Sales in the U.S., 2012 to 2024

Note: Lines represent total domestic (U.S.) semen units sold annually, reported separately for dairy semen (dashed line) and beef semen (solid line). Dairy semen units declined approximately 30% over the period, from roughly 22 million units in 2012 to approximately 15 million units in 2024. Beef semen units increased approximately 483% over the same period, from roughly 2 million units in 2012 to approximately 12 million units in 2024. The growth in domestic beef semen sales is primarily attributed to U.S. dairy producers shifting from dairy sires to beef sires for a portion of their cow herd to produce Beef-on-Dairy (BxD) calves that command higher market prices than straightbred dairy calves. Values are reported in millions of units sold.

Source: National Association of Animal Breeders (NAAB), Semen Sales Report, 2012–2024.

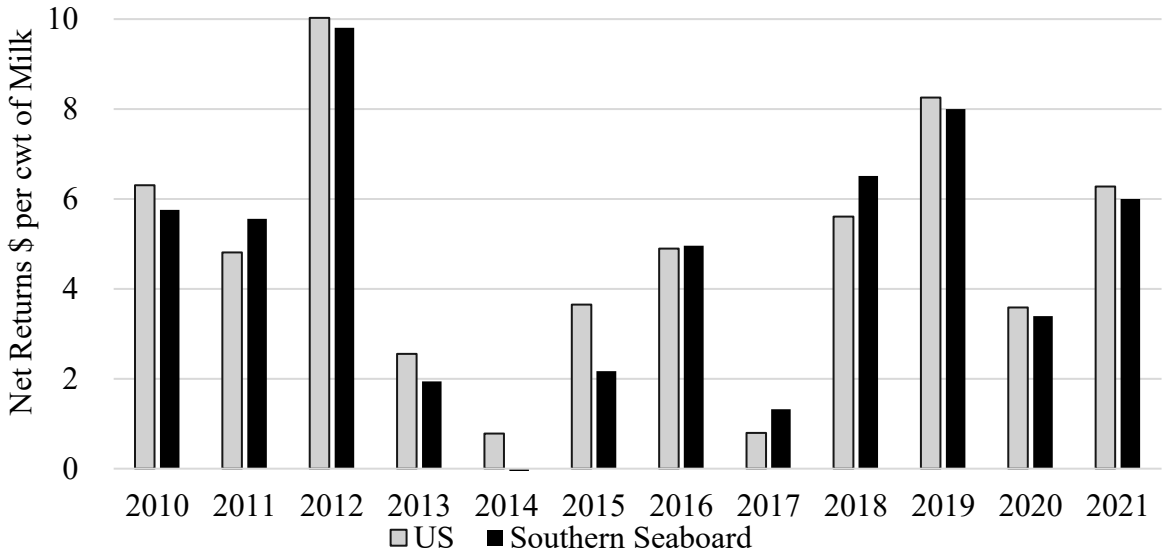


Figure 2-2. Average Net Returns per Hundredweight (CWT) of Milk Production by USDA ERS Region, United States and Southern Seaboard, 2010-2021

Note: Bars represent average annual net returns per hundredweight (cwt) of milk produced, as reported by the USDA Economic Research Service (ERS) Commodity Costs and Returns dataset. The U.S. average (light gray bars) includes all reporting dairy operations nationally. The Southern Seaboard region (dark gray bars) includes Virginia, North Carolina, South Carolina, Georgia, Florida, Alabama, Mississippi, Tennessee, Kentucky, Arkansas, and Louisiana. Net returns are reported in nominal dollars per cwt.

Source: USDA Economic Research Service, Commodity Costs and Returns, 2010–2021.

Table 2-1. Beef-on-Dairy (BxD) Market Locations and Augmented Dickey-Fuller (ADF) Unit Root Test Results for Weekly Volume-Weighted Average Beef-on-Dairy Auction Prices, First Differences, April 2024–March 2026

Market	Location	Z(t) Statistic	p-value	Result
MKT_1781	Clovis, NM	-7.794	<0.001***	I(1)
MKT_1784	Portales, NM	-7.46	<0.001***	I(1)
MKT_1908	New Holland, PA	-6.283	<0.001***	I(1)
MKT_1917	Greencastle, PA	-6.159	<0.001***	I(1)
MKT_1918	Middleburg, PA	-6.147	<0.001***	I(1)
MKT_1919	New Holland, PA	-7.579	<0.001***	I(1)
MKT_1953	Dalhart, TX	-7.762	<0.001***	I(1)
MKT_1955	Amarillo, TX	-7.796	<0.001***	I(1)
MKT_1970	Shipshewana, IN	-0.707	0.845	I(2)
MKT_1974	Canandaigua, NY	-3.945	0.002***	I(1)
MKT_1976	Indianapolis, IN	-5.044	<0.001***	I(1)
MKT_2011	Albany, NY	-6.112	<0.001***	I(1)
MKT_2027	Sioux Falls, SD	-7.501	<0.001***	I(1)
MKT_2041	Springfield, IL	-7.925	<0.001***	I(1)
MKT_2046	Greenville, IL	-6.677	<0.001***	I(1)
MKT_2167	Des Moines, IA	-7.646	<0.001***	I(1)
MKT_2193	Frankfort, KY	-6.958	<0.001***	I(1)
MKT_2199	Smiths Grove, KY	-6.269	<0.001***	I(1)
MKT_2528	Kalona, IA	-4.906	<0.001***	I(1)

Note: ***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively.

Each row represents a USDA AMS-reported livestock auction market where BxD steers and heifers were voluntarily identified in transaction records. Weekly volume-weighted average prices were calculated at the market level using headcount as the weighting variable. Markets were required to have a minimum of 50 weekly price observations to be included. The ADF test was applied to the first-differenced price series to confirm stationarity (integration of order one, I(1)). The null hypothesis of the ADF test is that the series contains a unit root (non-stationary). A result of I(1) indicates that the series was non-stationary in levels but became stationary after one round of differencing. MKT_1970 (Shipshewana, IN) failed to reject the null hypothesis in

first differences ($p = 0.845$), indicating the series was I(2), and was excluded from subsequent analysis. The remaining 18 markets across 9 states were retained for the VECM estimation.

Source: USDA Agricultural Marketing Service, Livestock Mandatory Reporting auction data, April 2024–March 2026. Authors' calculations conducted in Stata.

Table 2-2. Johansen Trace Test Results for Cointegrating Rank among 18 U.S. Beef-on-Dairy (BxD) Auction Markets, April 2024–March 2026

Rank	Eigenvalue	Trace Statistic	5% Critical Value	Decision
0	—	1575.48	—	Reject H_0
1	0.948	1268.23	—	Reject H_0
2	0.898	1030.97	—	Reject H_0
3	0.805	860.92	—	Reject H_0
4	0.753	715.55	—	Reject H_0
5	0.719	583.47	—	Reject H_0
6	0.641	476.81	—	Reject H_0
7	0.597	382.29	277.71	Reject H_0
8	0.573	293.83	233.13	Reject H_0
9	0.494	222.94	192.89	Reject H_0
10	0.411	167.84	156	Reject H_0
11	0.362	121.06	124.24	Fail to Reject

Note: Trace statistics for ranks 0 through 6 far exceed tabulated critical value bounds and are therefore reported without corresponding critical values (indicated by dashes). The cointegrating rank is selected at the first rank where the trace statistic fails to exceed the 5% critical value. The test identifies 10 cointegrating relationships among the 18 markets, meaning the system shares 10 common long-run equilibrium relationships and is driven by 8 common stochastic trends (18 variables minus 10 cointegrating vectors).

Source: Authors' calculations using USDA AMS auction data, conducted in Stata.

Table 2-3. Overall Model Fit Statistics for the 18-Market Vector Error-Correction Model of U.S. Beef-on-Dairy (BxD) Auction Prices, April 2024–March 2026

Model Statistics	Value
Number of observations	104
Log likelihood	-6,408.17
AIC	147.27
HQIC	160.15
SBIC	179.06
Det(Sigma_ml)	2.16E+31

Note: This table reports system-level fit statistics for the VECM estimated with a cointegrating rank of 10 and 3 lags across 18 endogenous market price series. The number of observations (104) reflects weekly data from April 2024 through March 2026 after accounting for lags. AIC (Akaike Information Criterion), HQIC (Hannan-Quinn Information Criterion), and SBIC (Schwarz Bayesian Information Criterion) are model selection criteria; lower values indicate better fit relative to model complexity. Det(Sigma_ml) is the determinant of the maximum-likelihood estimate of the residual covariance matrix. The log likelihood provides the basis for the Johansen trace test and information criteria calculations. Each of the 18 market equations contained 65 parameters (10 error-correction terms, 54 lagged price-change coefficients from 18 markets × 3 lags, and 1 constant). The ratio of observations to parameters (104:65) is below the commonly recommended 10:1 guideline (Greene, 2018), which is discussed as a potential limitation in the text.

Source: Authors' calculations using USDA AMS auction data, conducted in Stata.

Table 2-4. Equation-Level Results for the 18-Market Vector Error-Correction Model of U.S. Beef-on-Dairy (BxD) Auction Prices, April 2024–March 2026

Market	Location	RMSE	R^2	χ^2	p-value
MKT_1781	Clovis, NM	36.27	0.889	281.51	<0.001***
MKT_1784	Portales, NM	44.44	0.879	253.71	<0.001***
MKT_1908	New Holland, PA	5.92	0.886	272.68	<0.001***
MKT_1917	Greencastle, PA	7.75	0.733	96.04	0.007***
MKT_1918	Middleburg, PA	5.89	0.718	89.29	0.025**
MKT_1919	New Holland, PA	8.95	0.915	375.46	<0.001***
MKT_1953	Dalhart, TX	19.97	0.981	1810.53	<0.001***
MKT_1955	Amarillo, TX	40.19	0.924	427.72	<0.001***
MKT_1974	Canandaigua, NY	3.86	0.823	163.07	<0.001***
MKT_1976	Indianapolis, IN	101.49	0.764	113.38	<0.001***
MKT_2011	Albany, NY	24.87	0.772	118.68	<0.001***
MKT_2027	Sioux Falls, SD	19.79	0.805	144.23	<0.001***
MKT_2041	Springfield, IL	8.47	0.87	234.03	<0.001***
MKT_2046	Greenville, IL	7.06	0.739	98.84	0.004***
MKT_2167	Des Moines, IA	22.84	0.872	239.25	<0.001***
MKT_2193	Frankfort, KY	33.61	0.841	184.6	<0.001***
MKT_2199	Smiths Grove, KY	22.7	0.873	240.56	<0.001***
MKT_2528	Kalona, IA	2.45	0.881	258.13	<0.001***

Note:***,**,* represent significance at the 1%, 5%, and 10% level, respectively. Each row represents one equation in the VECM system, corresponding to a single BxD auction market. All 18 equations were statistically significant. R^2 values ranged from 0.718 (Middleburg, PA) to 0.981 (Dalhart, TX). Model stability was confirmed via the eigenvalue condition: the VECM produced exactly 8 unit moduli (18 variables minus 10 cointegrating vectors), and all remaining eigenvalues had modulus strictly less than 1 (range: 0.16 to 0.98), confirming dynamic stability. The Portmanteau Q-test at 4 lags confirmed no evidence of residual autocorrelation.

Source: Authors' calculations using USDA AMS auction data, conducted in Stata.

Table 2-5. Weak Exogeneity Test Results for Price Leadership Identification among 18 U.S. Beef-on-Dairy (BxD) Auction Markets, April 2024–March 2026

Market	Market Location	$\chi^2(10)$	p-value	Role
MKT_2046	Greenville, IL	5.44	0.860	Price Leader
MKT_2011	Albany, NY	14.8	0.140	Price Leader
MKT_1784	Portales, NM	16.66	0.082*	Price Leader
MKT_2193	Frankfort, KY	20.6	0.024***	Price Follower
MKT_2041	Springfield, IL	21.92	0.016**	Price Follower
MKT_2027	Sioux Falls, SD	23.22	0.010***	Price Follower
MKT_1955	Amarillo, TX	23.76	0.008***	Price Follower
MKT_1976	Indianapolis, IN	24.67	0.006***	Price Follower
MKT_1781	Clovis, NM	26.35	0.003***	Price Follower
MKT_1918	Middleburg, PA	26.59	0.003***	Price Follower
MKT_1919	New Holland, PA	28.95	0.001***	Price Follower
MKT_2199	Smiths Grove, KY	33.25	<0.001***	Price Follower
MKT_1974	Canandaigua, NY	35.33	<0.001***	Price Follower
MKT_1917	Greencastle, PA	36.3	<0.001***	Price Follower
MKT_1953	Dalhart, TX	38.19	<0.001***	Price Follower
MKT_2528	Kalona, IA	42.06	<0.001***	Price Follower
MKT_1908	New Holland, PA	46.35	<0.001***	Price Follower
MKT_2167	Des Moines, IA	47.3	<0.001***	Price Follower

Note:***,**,* represent significance at the 1%, 5%, and 10% level, respectively. Each row reports the results of a weak exogeneity test for one market in the VECM system. Three markets were identified as price leaders: MKT_2046 (Greenville, IL) and MKT_2011 (Albany, NY) at the 5% significance level. MKT_1784 (Portales, NM) was significant at the 10% level but not the 5% level and was still deemed a price leader for this study. The remaining 15 markets rejected the null hypothesis at the 5% level, identifying them as price followers

Source: Authors' calculations using USDA AMS auction data, conducted in Stata. Weak exogeneity tests follow Johansen (1992).

Vita

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