Meat and Muscle Biology™

Wet Aging USDA Select Beef Strip Steaks: Implications on Consumer Acceptability, Demand, and Product Selection

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Abstract: The objective of this study was to determine if wet aging increases the value and demand for lower-quality USDA-grade beef steaks. USDA Select boneless beef loins (NAMP #180) were dorsally divided into 4 equal portions, which were randomized to receive 0, 7, 14, or 21 d of wet aging. A total of twenty 2.5-cm-thick steaks from each aging time ($n = 20$ steaks per aging treatment) were cooked to an internal temperature of 71°C, cubed, and served to a consumer panel ($N = 126$), which evaluated acceptability using a 9-point hedonic scale with 1 and 9 representing "dislike extremely" and "like extremely," respectively. Immediately after the panel, a elicitation mechanism auction method was used to obtain independent consumer willingness to pay for each aging time. Consumers were separated into 6 clusters based on overall acceptability ratings. Cluster 1 ($n = 24$) preferred steaks that were aged for 0 and 21 d ($P \leq 0.014$). Cluster 2 ($n = 50$) liked all treatments moderately but liked steaks aged for 7, 14, and 21 d more than 0-d aged steaks ($P \leq 0.018$); Cluster 3 ($n = 20$) preferred 0-d steaks over 7-d steaks and 7-d steaks over 14-d and 21-d aged steaks ($P \leq 0.044$). Cluster 4 preferred 7-d and 21-d aged, and Cluster 6 preferred 14-d and 21-d aged steaks. Demand analysis indicated that 0, 7, and 21 d of aging would sell 5.29, 5.34, and 6.94 more units (0.454 kg) ($P < 0.001$) than steaks aged for 14-d holding price constant at the current market value of $14/0.454 kg. Overall, results indicated that wet aging for 14-d was not sufficient to provide the flavor and tenderness improvements that were apparent after 21 d of aging. Under optimal pricing and various cost scenarios, 21 d of aging was the most profitable single product offering only if daily production costs were sufficiently low.

Keywords: wet aging, beef, consumer acceptability, willingness-to-pay, optimal pricing
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Introduction

For beef palatability attributes, both texture and flavor assume pivotal roles due to their impacts on consumer acceptance, willingness-to-pay (WTP), and ultimately the profit margin (Corbin et al., 2015; Dinh et al., 2018). Wet aging is a commonly used method within beef production, involving the vacuum-packaging and refrigeration of meat (Martinez et al., 2017). Wet aging enhances beef tenderness and impacts the beef flavor profile through changes in water-soluble flavor compounds (WSFC; Dinh et al., 2018; Ha et al., 2019). Nevertheless, it is important to note that wet aging can exert a dampening effect on flavor acceptability for lean beef by influencing the concentrations of WSFC.

In addition, leaner beef is more susceptible to off-flavor, proteolysis, and protein oxidation. Therefore, the transformations in WSFCs have tangible consequences on consumers' liking and acceptability of beef products. Evers et al. (2020) stated that wet aging could increase bitterness and other off-flavors in cooked strip loins (*longissimus lumborum*) of Australian cattle, thereby diminishing how much the consumers liked the flavor. Similar observations have been reported in other studies as well (Brewer and Novakofski, 2008; Maughan et al., 2012). As wet aging leads to changes in beef flavor by triggering changes in WSFCs, its impact on sensory perception of lean beef increases since lean beef depends more on WSFC than fatty acids for its cooked flavor notes (Dinh et al., 2018).

Wet aging effects on WSFC introduce complexities that impact consumer acceptability and by extension consumer valuation and ultimately consumer demand. Lean beef categorized as USDA Select or lower constitutes approximately 24% of the U.S. beef market (Eastwood et al., 2017), and thus, research conducted to improve the value of lower quality meat products is warranted in order to add value to lean beef for health-conscious consumers. Beef consumer acceptability studies have yet to explore the linkages between beef aging, WTP, and subsequent consumer demand (Viljoen et al., 2002; Robbins et al., 2003; Zakrys et al., 2009). To explore these interrelationships more comprehensively, the current study combined sensory evaluation techniques and experimental auction methodologies to identify the influence of wet aging on both consumer acceptability and demand for USDA Select beef strip steaks.

Since wet aging is a time-dependent and costly process, there may exist an optimal length of aging for firms to improve profitability. Regarding revenue, WTP monetizes consumers' preferences and determines their purchase intent (Ajzen and Driver, 1992; Jaeger and Harker, 2005). This metric offers insights into the values, which consumers attach to a product and its distinctive characteristics (Sukumaran et al., 2019). Notably, while liking-based evaluations are informative, WTP provides a more tangible indicator of the likelihood of purchase at a given price, transcending mere preferences (Lawless et al., 2015). Individual and independent WTPs are often elicited via subject bids submitted in separate auctions (Lusk and Shogren, 2007). Consumer demand aggregates can be estimated more effectively through observed quantity sold and price fluctuations rather than attempting to discern individual WTP (Shogren et al., 2001). By aggregation of independent within-product bids, unit demands can be constructed delineating the quantity of individuals willing to procure each product across a specified price range (Alfnes et al., 2006; Lusk, 2010; Sukumaran et al., 2019). Unit demand is so called as each potential consumer purchases only one specified unit of the product. After mapping WTP to unit demand, production costs and product profitability can be evaluated. This will allow us to evaluate the overall objective of this research, which is to determine if wet aging increases the value and demand for lower-quality USDA Select beef steaks.

Materials and Methods

Experimental design

Wet aging process. A total of 20 boneless beef loins (NAMP #180) classified as USDA Select grade were purchased from a commercial packing plant. The loins were dorsally divided into 4 equal portions of at least 6.3 cm in thickness from the anterior to posterior, each of which was randomly assigned to 1 of 4 aging treatment durations: 0, 7, 14, or 21 d. The leftover loin with a small *longissimus* muscle was discarded. Each portion was then cut into 2.5-, 2.5-, and 1.3-cm steaks in that order from the anterior to posterior of the portion. Only the second 2.5-cm steak was used for this study to determine consumer acceptability.

The individual steaks were vacuum-packaged and labeled by their designated aging treatments. These packaged steaks were stored 2°C to 4°C in the dark. Upon completion of the aging duration, the steaks were promptly frozen at −20°C to halt further changes and were held in this frozen state until consumer sensory evaluation and WTP studies were conducted.

Consumer sensory evaluation. This study was approved by the Institutional Review Boards for the Protection of Human Subjects in Research (IRB #20–331) at Mississippi State University. Frozen steaks were thawed for 24 h prior to consumer sensory evaluation. After being trimmed of external fat and connective tissues, the steaks were meticulously enveloped in aluminum foil prior to cooking in a convection oven (VGRC605-6G-SS, Viking, Greenwood, MS) to an internal temperature of 71°C. Following the cooking process, a 3-min resting interval was observed, after which the steaks were segmented into 6 cubes measuring 1.3 cm × 1.3 cm × 2.5 cm each. These servings were presented to groups of 6 consumers within a 10-min timeframe. The samples were served in plastic cups (59.2 mL Plastic Cup, 200PC, Dart, Mason, MI) with a lid (Clear Plastic Lid, L2N, Dart, Mason, MI). Each cup was labeled with a 3-digit code. The consumer panel was comprised of a total of 130 consumer participants randomly selected from students, staff, and faculty at Mississippi State University. Their task involved evaluating the appearance, aroma, flavor, texture, and overall acceptability of beef steaks on a 9-point hedonic scale ranging from 1, indicating "dislike extremely," to 9, signifying "like extremely" (Civille and Carr, 2015). Each participant was furnished with a tray that held the coded steak samples, alongside provisions of water, apple juice, unsalted crackers, and a receptacle for expectoration. To ensure a neutral palate between tastings, the participants were instructed to cleanse their palate with apple juice, water, and unsalted crackers after each sample assessment. The sensory evaluation and auction were completed in 2 d with 11 sessions per day (6 consumers per session, 4 consumers in the last one). Consumers completed sensory evaluation in the individual sensory booth. The following auctions were conducted in a separate conference room to ensure no interruption between sessions.

Consumer willingness-to-pay. This experiment was conducted under the same IRB approval listed under section 2.1.2 (IRB #20–331). Immediately following sensory evaluation, the WTP experiment was conducted, which serves as the building block for unit demand. Recognizing that individuals tend to inflate their WTP within a hypothetical context (List and Gallet, 2001), this study employed a non-hypothetical auction methodology to obtain WTP estimates (Chang et al., 2009). The Becker–DeGroot–Marschak (BDM) auction was administered for its relative accuracy in revealing a subject's true intrinsic valuation of a product to the experiment's auctioneer, yielding results comparable to other auction mechanisms for one-time solicitations (Lusk and Shogren, 2007; Lusk et al., 2007). Consumer demand estimates generated from the distribution of BDM bids have been shown to be more stable and reliable across the same consumer groups over time, even though individual WTP are unstable across time (Alfnes et al., 2006).

Participant auction instructions and bidding record sheets are designed to be straightforward, catering to inexperienced bidders (Lusk and Shogren, 2007). A brief discussion of the WTP experiment is as follows. To begin, each participant was instructed to retain their sensory evaluation record sheet to aid their memory of their acceptability ratings before placing their bids for each steak product. Participants were given explicit written and verbal instructions outlining the auction procedure followed by example bidding and explanations of earnings and ending with fielding participant questions. To facilitate their bidding efforts, participants were furnished with a $21.00 voucher to secure a 12-oz (0.34 kg) prepackaged portion of steak, which served as the specified unit of size for the demand analysis. This voucher could be redeemed at the university's food store. To mimic how steaks are sold in the grocery stores in the United States, participants were given explicit instructions to place a single bid for each product in terms of $/pound, ranging from $0 to $28 in 1-cent increments. This range was centered around $14/pound, an approximate prevailing local market price of beef steaks between March and May 2022. The selection of bid range was selected to match a reasonable and symmetric range of prices asked by sellers as well as mitigate left ($b^* < 0$) and right ($b^* > 28$) censoring of their true bid if allowed to submit (b^*).

At the conclusion of each session, a market price was randomly drawn from a uniform distribution for each product ranging from $0 to $28/pound in 1-cent increments. If a participant submitted a bid equal to or greater than the market price, they became eligible to obtain that specific serving of steak at the market price. In situations where a participant qualified for more than one serving, a randomized decision was made by the experimenter to determine which serving they would receive. This approach ensured independent valuations and sidestepped the complexities linked with demand reduction, as highlighted by Ausubel et al. (2014). In the case of winning a steak, the market price was then adjusted to a total cost for the 12 oz serving and subtracted from the $21.00 stipend. Due to the constraints on the availability of the experimental product, participants who won a steak were furnished with a comparable steak from a commercial brand. Any remaining balance on the voucher was returned to the participant. If a participant did not win any serving, they retained the full value of $21.00 on the voucher.

Data Analysis

Consumer sensory evaluation

Sensory data were analyzed in a general linear mixed model with aging time as a fixed effect and panelist as a random effect. Analysis of variance was performed in the MIXED procedure of SAS v. 9.4 (SAS Inst. Inc., Cary, NC). Means, when different, were separated by a protected *t*-test in the LSMEANS option of the MIXED procedure. Actual probability values were reported. Cluster analysis was conducted using Ward's method within the agglomerative hierarchical clustering procedure in XLSTAT 2018.2.50198

Unit-demand comparisons

Participant bids submitted for each product in the WTP experiment were utilized to construct product-specific stepwise unit-demand functions as in Sukumaran et al. (2019) or, alternatively, the inverse unit demands as in Alfnes et al. (2006) and Lusk (2010). Unit-demand functions were constructed by means of the following thought experiment. Deriving the demanded quantity for each product is tantamount to the count of N active consumers who submit a bid that is greater than or equal to any given price offered by a seller within a series of incremental price steps ranging from \$0 to \$28.00/0.454 kg. As such, the unit demand takes the form of a probabilistic survival distribution with a quantity intercept equal to the number of potential consumer purchases at a price offer of zero. Unit demand can generally be expressed by Equation (1) as follows, where N represents the total number of active consumers multiplied by the survival distribution $[1 - F(p)]$ at any given price offering (p).

$$Q(p) = N[1 - F(p)] \tag{1}$$

This function is decreasing in price and becomes smoother and approximately more continuous as N bids for a single unit increase, as well as decreasing in the length of the price increment.

The first methodological approach for comparing product unit demands follows directly from Sukumaran et al. (2019). The data used for this analysis are constructed from the previous thought experiment generating stepwise unit-demand functions by setting the price increment equal to 1 cent per 0.454 kg. The estimation of a representative unit demand for aged beef steaks is expected to employ a fourth-degree price polynomial in price offerings to represent the expected shape of the unit demand along with product-specific intercept dummy variables to test for overall differences in demand. An ordinary least-squares regression was conducted using the REG procedure in SAS v. 9.4. The final choice of polynomial was determined by evaluating for best model fit and parameter significance. Additional pairwise demand comparisons between treatment regressors are tested by means of F-tests in the REG procedure. It is important to note that a polynomial form of demand serves as a close approximation without placing restrictions on the true underlying individual utility functions. However, the polynomial does create a functional form restriction.

To address the possible functional form restrictions of the polynomial and provide a methodological comparison, the study further tests for price interval differences between any pair of product demand distributions. Doing so facilitates a more flexible and complete approach to detecting differences in demand along the price/valuation spectrum. Differences in demand identified via overall intercept shifters cannot identify price interval distributional differences. For example, between any 2 demands with nearly identical means and/or intercepts, there may exist a particular subset of prices equal to the bidder valuations having significant differences in demand that may or may not influence overall demand differences. Therefore, unique bidder valuations can be identified as the leading driver (or not) of possible shifts in overall demand. The nonparametric Kolmogorov-Smirnov (KS) test was employed in the Npar1way procedure in SAS v. 9.4. The KS procedure compares the empirical cumulative distributions (Empirical Distribution Function (EDF) option), which represents the empirical inverse unit demands, $F(p)$ in Equation (1). Both methodological approaches, however, are expected to yield consistent results regarding the detection of major differences between product demands.

Hypothetical single-product offering under optimal pricing

In the initial steps of new product development, firms are not only concerned with which product receives acceptable sensory ratings and/or the highest level of demand but also which product may return the highest profit. For instance, it is possible that a product may be superior in every sensory category and clearly generate the greatest overall demand. However, it is also possible that to deliver such a product may be cost-prohibitive.

To illustrate this dilemma, the firm may consider selling one of the products to N active consumers by setting a take-it-or-leave-it output (aka reservation) price. Following Rasmusen (1989), let the ith steak product's total profit (p_i) be derived from the expected sale of steak type i at a particular price (p_i) given per unit cost of production (c_i), where i equals 0-d, 7-d, 14-d, and 21-d aging periods that are depicted in Equation (2). The profit-maximizing output price (p_i^*) is provided in Equation (3).

$$\pi(p_i) = (p_i - c_i)N[1 - F(p_i)] \tag{2}$$

$$p_i* = c_i + \frac{1 - F(p_i*)}{f(p_i*)} \tag{3}$$

Both equations require either an assumption or estimation of the underlying bid distribution for each product $f(b_i)$, which is supplanted with notation $f(p_i)$ as bidders are assumed to purchase when indifferent between their bid and price. The resulting demand (survival) function $[1 - F(p_i)]$ is derived from the underlying bid distribution. The ratio of the 2 distributions in Equation (3) generates the profit-maximizing markup over costs. Also note that p_i^* is independent of N as the optimal markup is determined by the ratio of the likelihood of a sale to all possible prices equal to bids at p_i. Though bids are recorded in \$/pound, the results are reported in \$/0.454 kg.

Given that the data consist of fewer than 2,000 observations, a normality test of the bidding distributions was conducted using the Shapiro-Wilk test in the Univariate procedure in SAS v. 9.4. When the test failed to reject normality, the normal distribution was utilized. If normality was rejected, further distributional tests were conducted to find a better-fitting distribution (e.g., Weibull, Gamma, and Beta) by means of the Hpseverity procedure in SAS v. 9.4.

Results and Discussion

Consumer sensory evaluation

Results are based on 126 observations since 4 panelists did not fully complete their sensory evaluation questionnaires. On average, consumers exhibited a preference for the aroma of 14-d steaks ($P = 0.041$) over day 0 steaks (Table 1), but no other differences existed in aroma acceptability among treatments. The flavor of 7-d steaks ($P = 0.031$) was preferred over 14-d aged steaks but did not differ from day 0 and 21 steaks. The texture of 21-d steaks ($P = 0.034$) was preferred over 0-d and 14-d steaks but did not differ from 7-d aged steaks. On average, no differences existed in overall acceptability and appearance.

Since consumers were highly variable in their acceptability ratings of the steak treatments, the 126 participants in the consumer evaluation were grouped into 6 clusters based on their overall acceptability ratings for wet-aged beef steaks (Table 2). Cluster 1 ($N = 24$; 19% of consumers) preferred 0-d and 21-d aged steaks over 7-d and 14-d aged steaks. The 0- and 21-d aged steaks were liked between slightly and moderately, the 14 d steaks were rated between neither like nor dislike and like slightly, and the 7-d aged steaks were disliked slightly. Consumers in Cluster 2 ($N = 50$; 40% of the consumers) rated the flavor, texture, and overall acceptability of steaks that were wet-aged steak for 7, 14, and 21 d between "like moderately" and "like very much." In addition, they preferred beef steaks in these 3 treatments when compared to 0-d aged beef steaks ($P \leq 0.044$), which were still liked between slightly and moderately. This was the largest group of consumers and all panelists in this cluster liked the steak treatments. Consumers in Cluster 3 ($N = 20$; 16% of the consumers) preferred steaks ($P \leq 0.044$) that were not aged and aged for 7 d over those aged for 14 and 21 d with respect to overall acceptability, texture acceptability, and flavor acceptability. In addition, acceptability for steaks decreased for these consumers as aging time increased. Cluster 4 ($N = 14$), which included 11% of the consumers, preferred steaks that were aged for 7 or 21 d ($P \leq 0.016$) and rated these treatments as "like slightly." Additionally, consumers in this group rated 14-d aged beef steaks as "dislike slightly" and rated them as less acceptable ($P \leq 0.046$) than all other treatments. Consumers in Cluster 5 ($N = 10$; 8 % of the consumers) "did not like any of the steak treatments." Though it is unknown why these consumers did not like steak, it may have been because consumers may prefer their steaks to be prepared using

Table 1. Mean scores[1] for consumer acceptability ($N = 126$) of wet-aged beef steaks of consumer segments using a hedonic scale

	Treatment					
Attribute	0 d	7 d	14 d	21 d	SEM	*P* value
Appearance	5.8	5.8	5.8	6.0	0.131	0.172
Aroma	5.8^{b}	5.9^{ab}	6.1^{a}	5.9^{ab}	0.098	0.041
Flavor	6.2^{ab}	6.3^{a}	5.9^{b}	6.1^{ab}	0.130	0.031
Texture	6.2^{b}	6.3^{ab}	6.0^{b}	6.7^{a}	0.147	0.034
Overall	6.1	6.1	6.0	6.3	0.123	0.134

[1]Scores were based on a 9-point hedonic scale (1 = dislike extremely, 2 = dislike very much, 3 = dislike moderately, 4 = dislike slightly, 5 = neither like nor dislike, 6 = like slightly, 7 = like moderately, 8 = like very much, and 9 = like extremely).

[a–c]Means with the same letter within each row are not significantly different ($P < 0.05$).

Table 2. Clustering of 126 consumers based on their overall acceptability[1] of wet-aged beef steaks

Clusters[2]	Consumer (*N*)	Overall acceptability 0 d	7 d	14 d	21 d	SEM	*P* value
1	24 (19%)	6.6[a]	4.1[c]	5.6[b]	6.3[a]	0.25	≤0.013
2	50 (40%)	6.8[b]	7.2[a]	7.2[a]	7.5[a]	0.13	≤0.044
3	20 (16%)	7.6[a]	6.8[b]	6.0[c]	5.0[d]	0.22	≤0.015
4	14 (11%)	5.2[b]	6.0[a]	3.9[c]	6.4[a]	0.28	≤0.003
5	10 (8%)	3.1[bc]	4.0[ab]	4.1[a]	2.5[c]	0.34	≤0.032
6	8 (6%)	2.6[c]	4.8[b]	6.3[a]	6.3[a]	0.28	≤0.004

[1]Consumer acceptability was evaluated on a hedonic scale, in which 1 = dislike extremely, 2 = dislike very much, 3 = dislike moderately, 4 = dislike slightly, 5 = neither like nor dislike, 6 = like slightly, 7 = like moderately, 8 = like very much, and 9 = like extremely.

[2]Cluster analysis was conducted using Ward's method within the agglomerative hierarchical clustering procedure in XLSTAT based on overall acceptability ratings by panelists.

[a–c]Means with the same letter within each row are not significantly different ($P < 0.05$).

a different cooking method, with salt and pepper, and/or with other spices than that which was used in the current study. Like Cluster 2, consumers in Cluster 6 ($N = 8$; 6% of the consumers) preferred steaks that were aged for 14 and 21 d over 0-d and 7-d aged steaks ($P \leq 0.025$) and only liked steak treatments that were aged for 14 and 21 d. Based on cluster analysis, 94 out of the 116 panelists that liked steak rated the 0-d aged treatment as like slightly (6) or greater, and 84, 78, and 96 liked 7, 14, and 21-d aged steaks slightly or greater. This indicates that the day 0 and 21 steaks were acceptable to a greater number of consumers than the 7-d and 14-d aged steaks.

The consumers' perception and preference for meat are profoundly influenced by the distinct aroma and flavor characteristics of cooked meat (Lucherk et al., 2016; Dinh et al., 2018). The process of cooking meat is pivotal in rendering it palatable, leading to the formation of meat aroma and flavors through mechanisms that include the Maillard reaction, lipid oxidation, and thermal degradation of thiamine. These pathways bring about the interaction of various products, which are facilitated by WSFC such as free amino acids, peptides, reducing sugars, vitamins, unsaturated fatty acids, and nucleotides (Calkins and Hodgen, 2007; Dinh et al., 2018; Sukumaran et al., 2019). As reported by Dinh et al. (2018), the USDA quality grades such as USDA Prime, USDA Choice, and USDA Standard, has a significant impact on the WSFC that are present in bovine *longissimus lumborum* that have been wet-aged. Specifically, the contents of WSFC were found to be higher in the raw forms of USDA Choice and Standard grades and underwent more changes during the cooking process. In addition, another study by Smith et al. (2008) highlighted that USDA quality grades also exert a measurable influence on consumer perception and purchase intent. Their findings indicate that consumers tended to rate USDA Choice wet-aged steaks more favorably than their USDA Select counterparts. In the present study, consumer preference exhibited a marked inclination toward steaks aged for 7 and 21 d. As stated by Khan et al. (2015), postmortem wet aging induces notable changes in WSFC. Specifically, ribonucleotides undergo enzymatic degradation to produce free ribose, hypoxanthine, and phosphate. Concurrently, proteolytic processes result in an increase in free amino acids and peptides. These WSFC play an important role in shaping the flavor intensity and, consequently, the consumer eating experience. For instance, free amino acids are characterized by diverse taste profiles, including sweet, sour, and umami. Furthermore, short-chained peptides primarily contribute to bitterness, while inosine 5'-monophosphate (IMP) and guanosine 5'-monophosphate (GMP) are prominent contributors to the umami flavor profile (Tikk et al., 2006; Dinh et al., 2018). Interestingly, the Maillard reaction between ribose and amino acids can yield desirable roasted flavors. However, premature degradation of nucleotides can lead to an increased formation of hypoxanthine during cooking, potentially introducing undesirable bitter flavors (Koutsidis et al., 2008). This might explain why the 7-d aged steak was particularly favored; the shorter duration of postmortem metabolism in the 7-d aging period likely led to a higher concentration of IMP and GMP and a reduced presence of hypoxanthine when compared to steaks aged for 14 d.

Additional research underscores the efficacy of wet aging in enhancing key quality attributes of beef, such as tenderness and juiciness, both of which are intrinsically linked to consumer acceptability (Laster et al., 2008;

Dashdorj et al., 2015). Studies have revealed that extended periods of wet aging, ranging from 21 to 28 d, yield significantly improved scores in consumer evaluations for tenderness and juiciness compared to beef aged for shorter durations (7 to 14 d) (Laster et al., 2008; Dashdorj et al., 2015). In addition, Lepper-Blilie et al. (2016) suggested that wet-aging steaks for a period of 21 d or longer enhances their tenderness, thereby potentially increasing consumer satisfaction related to the eating experience, even for steaks with a marbling score below SM^{50}. These findings suggest that longer aging periods are more effective in optimizing meat characteristics that are pivotal to consumer satisfaction. In contrast, the influence of wet aging on the flavor profile of beef remains a subject of ongoing debate within the scientific community. Although a cohort of studies reports a positive correlation between the duration of wet aging and the development of enhanced flavor profiles (Ba et al., 2014; Neethling et al., 2016; Ha et al., 2019), other researchers have indicated that the impact on flavor is not significant (Smith et al., 2014). This discrepancy suggests that while wet aging may be a reliable method for improving the tenderness and juiciness of beef, its impact on flavor remains equivocal and warrants further investigation. Factors such as the specific cut of meat, USDA quality grade, aging conditions, and individual consumer preferences may all contribute to this observed variability.

Willingness-to-pay and unit demand

Overall, the WTP results were consistent with the overall acceptability cluster rankings in Table 2. Analysis of the mean bidding value within each consumer cluster over aging duration is provided in Table 3. The average bidding values for day 0 and day 21 in Cluster 1 ($N = 24$; 19% of consumers) were \$13.53/0.454 kg and \$13.48/0.454 kg, compared with \$9.83/0.454 kg and \$11.03/0.454 kg for day 7 and day 14, respectively ($P \leq 0.023$). Consumers in Cluster 2 ($N = 50$; 40% of consumers) placed a higher average bid for 7-d and 21-d aged steaks than 0-d aged steaks ($P \leq 0.033$), with average bids of \$15.59 and \$15.73/0.454 kg. However, consumers in Cluster 3 ($N = 20$; 16% of consumers) placed a higher bid for 0-d aged steaks as compared with other aging times ($P \leq 0.045$), with an average bid of \$17.65/0.454 kg. Like Cluster 2, consumers in Cluster 4 ($N = 14$; 11% of consumers) placed greater average bids for 7- and 21-d aged steaks than 0- and 14-d aged steaks ($P \leq 0.073$). There was no difference in average bids for Cluster 5 ($N = 10$; 8% of consumers; $P = 0.486$). Cluster 6 ($N = 8$; 6% of consumers) tended to place lower bids of \$8.78/0.454 kg for steaks aged for 0 d compared with steaks that were aged for 14 and 21 d ($P \leq 0.063$). Clusters 5 and 6 also gave lower bids for steaks than panelists in Clusters 1, 2, 3, and 4.

The enhanced meat quality delivered by wet-aged beef steaks translates into economic values, such as consumer WTP and subsequent unit demand. The stepwise unit demands constructed from the 126 bids per product in 1 cent increments are represented in Figure 1. The unit demands are consistent in shape with those reported by Sukumaran et al. (2019) as well as inverse unit demands observed for other food products as reported by Jaeger and MacFie (2010) and Alfnes et al. (2018).

The results from the unit-demand regression analysis of the data depicted in Figure 1 are tabulated in Table 4. The likelihood of bid censoring appeared minimal, with the highest level of possible right censoring (3.08%) for 21-d aged steaks and left censoring (2.31%) for 0-d aged steaks. Otherwise, left or right censoring was largely less than 1%. The modeling of the fourth-degree price polynomial with intercepts provided a strong model fit with the coefficient of determination (R^2) equal to 0.99. The base product comparator

Table 3. Mean bidding value (\$/0.454 kg) for individual aging time within each consumer cluster[1]

Clusters	Consumer (*N*)	Aging time 0 d	7 d	14 d	21 d	SEM	*P* value
1	24 (19%)	13.53[a]	9.83[b]	11.03[b]	13.48[a]	1.06	≤0.023
2	50 (40%)	13.96[b]	15.59[a]	14.54[ab]	15.73[a]	0.76	≤0.033
3	20 (16%)	17.56[a]	15.50[b]	11.48[c]	11.28[c]	1.00	≤0.045
4	14 (11%)	11.61[b]	14.06[a]	10.12[b]	15.43[a]	1.33	≤0.073
5	10 (8%)	7.30	8.37	9.17	7.85	1.88	0.486
6	8 (6%)	8.78[b]	9.81[ab]	11.27[a]	11.79[a]	1.27	≤0.063

[1]Cluster analysis was conducted using Ward's method within the agglomerative hierarchical clustering procedure in XLSTAT based on overall acceptability ratings by panelists.

[a–c]Means with the same letter within each column are not significantly different.

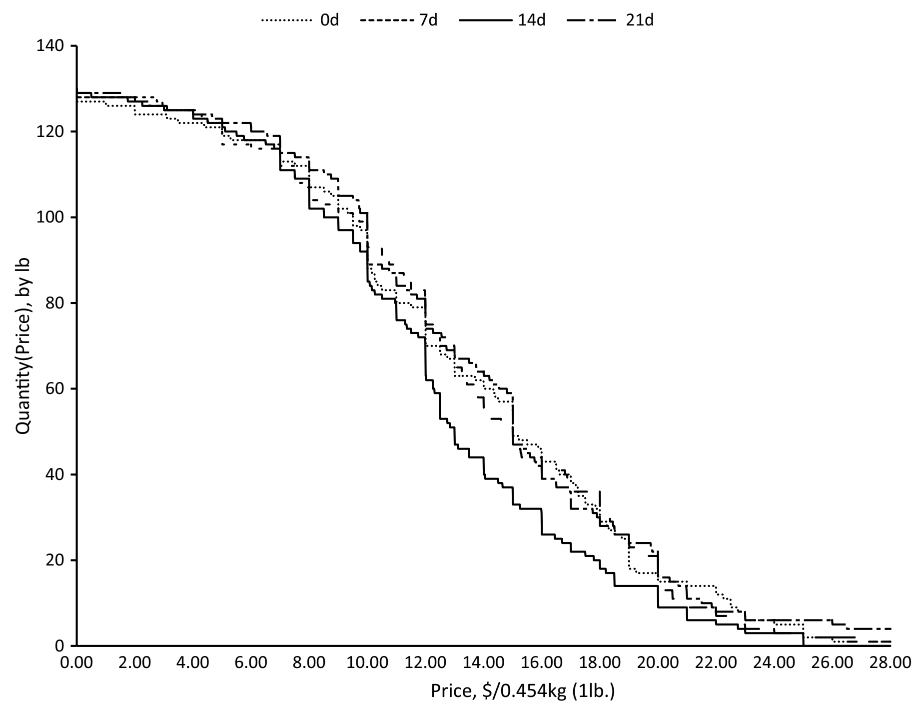

Figure 1. Constructed stepwise unit demands for $N\,[1 - F(p_i)]$ in Equation (1) of wet-aged beef strip steaks in 1-cent increments ($N = 2{,}801$ per product).

Table 4. Unit-demand regression analysis for wet-aged beef strip steaks ($N = 2{,}801$ per product constructed from 1 cent price intervals ranging from \$0 to \$28 using 130 recorded bids per product)[1]

Variables*	Coefficient	Standard error	*P* value
Intercept	117.79	0.19	<0.001
Price	5.65	0.09	<0.001
Price[2]	−1.31	0.01	<0.001
Price[3]	0.05	0.0007	<0.001
Price[4]	−0.0005	0.00001	<0.001
0 d	5.29	0.10	<0.001
7 d	5.34	0.10	<0.001
21 d	6.94	0.10	<0.001
***F*-test pairwise comparisons**			
0 d vs 7 d	—	—	0.60
0 d vs 21 d	—	—	<0.001
7 d vs 21 d	—	—	<0.001
$R^2 = 0.99$			

[1]Ordinary least-squares analysis conducted using REG procedure.

[2]Price squared.

[3]Price cubed.

[4]Price o the 4th power in the regression model.

*14 d is the basis of demand comparison.

for shifts in demand is 14-d aged steaks. All coefficients in the model were statistically significant, with *P*-values less than 0.001, indicating the robustness of the model in capturing the underlying relationships among the variables.

The polynomial form demand analysis reveals differences in consumer preference for steaks aged for varying durations. The 14-d steaks were chosen as the basis of comparison as they exhibited the lowest flavor, texture, and overall acceptability score. Specifically, the demand for steaks aged for 14 d was significantly less than all other aged steaks with their demanded quantity increasing 5.29, 5.34, and 6.94 units for 0, 7, and 21 d of aging (all $P = <0.001$) when compared to steaks that were aged for 14 d holding price equal to its mean (\$14.00/0.454 kg). This result is consistent with previous sensory results depicted in Table 1, primarily by a combination of reduced flavor and texture acceptability. From the F-tests, there was no significant difference between the demands of 0 and 7 d ($P = 0.60$), whereas the demand for 21 d aged is significantly greater than both 0 and 7 d ($P = <0.001$).

Results from the empirical distribution analysis of the stepwise unit demands depicted in Figure 1 are presented in Table 5. These results largely follow the polynomial form results in magnitude differences and significance as reported in Table 4. The only exception was significantly less units demanded for 0 d than 7 d of aged steaks at the price point of \$13.25 ($P = 0.001$), which is near the average price/value point of \$14.00/0.454 kg. Though generally there was no significant increase in overall unit demand for 7 as compared to 0 d of age from the

Table 5. Empirical $F(p_i)$ unit-demand distribution difference tests between wet-aged beef strip steak products ($N = 2{,}801$ per product constructed from 1 cent price intervals ranging from \$0 to \$28 using 130 recorded bids per product)[1]

Max deviation \$ price point[a]	Predicted quantity sold comparison[b]	Quantity difference (# units)	P value
13.25 < mean	0 d < 7 d	1.65	<0.0001
11.75 < mean	0 d > 14 d	5.28	<0.0001
Mean < 24.00	0 d < 21 d	1.66	0.002
10.00 < mean	7 d > 14 d	5.34	<0.0001
Mean < 19.01	7 d < 21 d	1.60	<0.0001
11.75 < mean	14 d < 21 d	6.94	<0.0001

[1]Kolmogorov-Smirnov tests conducted using the Npar1way procedure.

[a]The price the maximum deviation occurred relative to the mean price of \$14.00/0.454 kg.

polynomial method, there was a marked increase in demand for the average valued consumers of 1.65 units (or 1.27%). Relative to 14-d aged steak, 0-, 7-, and 21-d aged steak resulted in significantly greater demand of 5.28, 5.34, and 6.94 units (or 4.06%, 4.11%, and 5.34%) ($P = 0.001$) at price points below the average value. Therefore, the major improvement in overall unit demand appears to be driven by the greater demand of lower-value consumers. Finally, relative to 21-d aged steak, 0- and 7-d aged steak resulted in significantly lower demand of 1.66 and 1.60 units (or 1.28% and 1.23%) ($P = 0.002$ and 0.001) at price points above the average value consumer. Therefore, 21-d aged steaks maintained its advantage over its second-best products primarily from the higher-value consumers.

Overall, the findings suggested that both methodologies identify major shifts in demand, with 21 d of aging representing the most demanded product and 14 d the least. In addition, the findings were consistent with the results of the sensory evaluation, which indicated that the 0-, 7-, and 21-d aged steaks were acceptable to a greater number of consumers than the steaks that were aged for 14 d. The empirical distribution analysis, however, is more sensitive to differences in value segments of demand than the polynomial-intercept-only approach.

Optimal pricing

The Shapiro-Wilk tests of each steak product's underlying bid distribution failed to reject that any distribution was normally distributed (all $P \geq 0.168$) (no table reported). The relative ranking of mean bids is in agreement with the unit-demand analysis (no table reported). The mean bid from the WTP experiment for 0-d aged steak was \$13.47/0.454 kg with a standard deviation of \$5.93. The mean bid for 7-d aged steak was \$13.48/0.454 kg with a standard deviation of \$5.66. The mean bid for 14-d aged steak was \$12.33/0.454 kg with a standard deviation of \$5.10. Finally, the mean bid for 21-d aged steak was \$13.82/0.454 kg with a standard deviation of \$5.75.

Assuming normally distributed bids, the predicted unit demand for each product that was used in the solution process for Equations (2) and (3) is delineated in Figure 2. Product comparison results from a hypothetical single product offering are presented in Table 6. The optimal product choice is contingent upon various assumed constant marginal per unit production cost scenarios of aging steak per week and serves simply to elucidate the importance of considering marginal costs of production on product selection.

To begin, let the base production cost of the non-aged product (0 d) be equal to \$8.00/0.454 kg. This cost represents the required per unit production cost for the current real-world market price of \$14.00/0.454 kg to represent an optimal price for 0 d of aging. In each scenario analysis, the total cost of refrigeration (or utility costs) as steaks age increases at a constant rate; hence, marginal costs are constant. Scenario 1 assumes that the marginal cost of aging is \$0.05/0.454 kg per week. Under this marginal cost scenario, the most profitable product is aged for 21 d ($\pi_{21} = \$166$) with an optimal price of \$14.60 resulting in units sold 58/130. Note that 7d is more profitable than 0 d, indicating that with low "enough" marginal costs, even a small increase in demand, as indicated from the empirical demand analysis, may be influential in product selection. Scenario 2 posits marginal costs are \$0.13/0.454 kg per week. Under this scenario, both 0 and 21 d of aging yielded equivalent profits of \$157, where the 21-d product sells more quantity offsetting the higher marginal costs. Lastly, Scenario 3 assumes the marginal cost increases to \$0.20/0.454 kg per week. In this scenario, 0 d of aging generates the greatest total profit. In all marginal cost scenarios, 14 d of aging is the least profitable.

From these results, it is recommended that food companies engage in comprehensive cost analysis prior to making final product(s) selection to determine how marginal costs evolve over time. This should of course be complemented with both consumer preference and

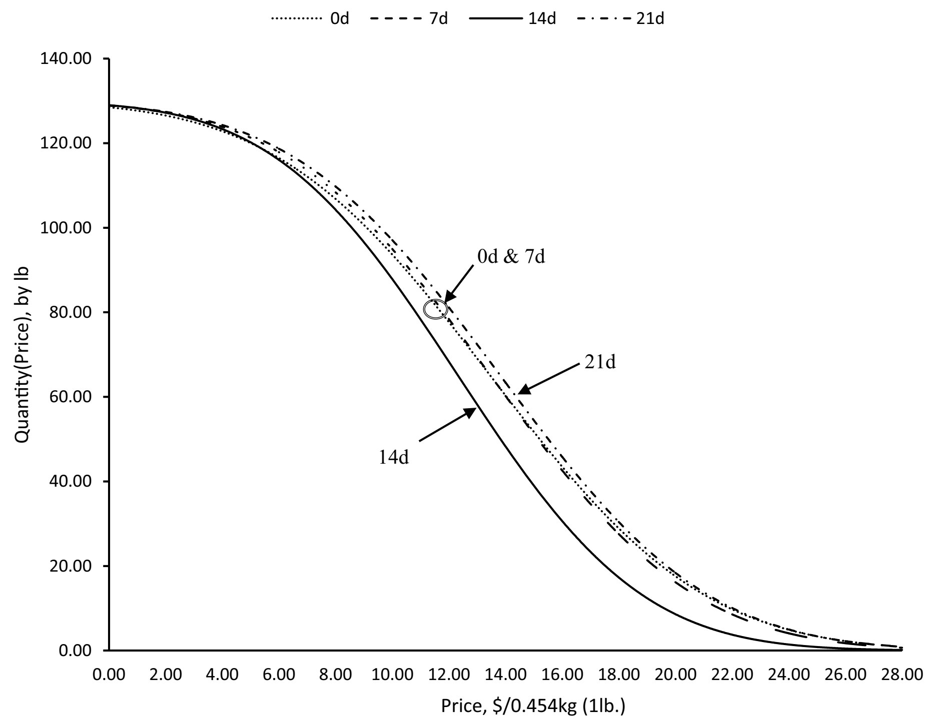

Figure 2. Predicted unit demands assuming normally distributed bids used for profit maximization Equations (2) and (3) for wet-aged strip steaks in 1 cent increments ($N = 2{,}801$ per product).

Table 6. Weekly cost increase scenarios identifying the profit-maximizing single product offering

Aging		Scenario 1 ($0.05/0.454 kg/week)					Scenario 2 ($0.13/0.454 kg/week)					Scenario 3 ($0.20/0.454 kg/week)			
Period	Product	c_i[a]	p_i*[b]	Q_i[c]	π_i[d]	Product	c_i[a]	p_i*[b]	Q_i[c]	π_i[d]	Product	c_i[a]	p_i*[b]	Q_i[c]	π_i[d]
0 d	1	8.00[1]	14.5	56	157	1**	8.00[1]	14.5	56	157	1**	8.00[1]	14.5	56	157
7 d	2	8.05	14.4	57	158	2	8.13	14.4	57	155	2	8.20	14.4	56	152
14 d	3	8.10	13.5	53	118	3	8.26	13.6	52	112	3	8.40	13.6	52	108
21 d	4**	8.15	14.6	58	166	4**	8.39	14.7	57	157	4	8.60	14.8	56	149

[1]$8.00/0.454 kg base cost for 0 d.

**Indicates the most profitable single product offering.

[a]Assumed costs increase ($/0.454 kg) for steak type *i*.

[b]The optimal price (p_i^*) in $/0.454 kg from Equation (2) for steak type *i*.

[c]The quantity of sale (Q*i*) in 0.454 kg single servings at the optimal price from Equation (1) where $N = 130$ for steak type *i*.

[d]Total maximum profit (π) in U.S. dollars from Equation (3) for steak type *i*.

demand analysis. It should also be noted that a more real-world benefit-cost analysis is beyond the scope of this study due to the unavailability of firm-level production cost data, including costs of refrigeration, freezer storage, utility equipment expenses, labor, transportation, interest, and the like.

The next step in the economics-based research is to consider multiproduct offerings of all 4 aged products, where consumers are allowed to freely choose a product that maximizes their gains. The reason being is that the major difference in aging costs is refrigeration time. This type of analysis would allow for the expected quantity sold per product to be dependent on the prices offered for each product. By setting a menu of optimal prices, additional profits over the single offering can be gleaned from those who value each product the most, including those who value 14 d of aging the most. Doing so poses computational challenges for the nonlinear gradient search across a large set of possible price combinations (approximately 2.56 E+12). The additional complexities arise due to the extreme nonlinearities of the joint profit maximization problem caused by the 4 underlying nonlinear demands and is thus left for further research.

Conclusions

This study demonstrated that wet aging serves as a significant determinant of consumer acceptability regarding flavor and texture, WTP, and demand for USDA Select *longissimus* steaks, warranting further exploration and optimization by the meat industry to meet consumer expectations effectively. Specifically, the data revealed that beef steaks aged for 21 d were most favorable in terms of both consumer acceptability and WTP, as well as a higher margin, whereas steaks aged for 14 d demonstrated reduced consumer acceptance and demand across various pricing scenarios. Moreover, this study indicated the importance of the interplay between texture and flavor in driving WTP and demand, thus underscoring the need for a multifaceted approach to optimizing beef quality for various consumer markets. These results indicate that focusing on overall acceptability (which was not different across aged products) may not fully reveal consumer preferences to the seller. Additionally, the present study introduced a method with enhanced sensitivity in gauging consumer responses to price changes and predicting the prospective market share of forthcoming products. Producers and retailers may benefit from fine-tuning their aging processes to better align with consumer expectations, thereby potentially increasing market share and profitability. For a more conclusive strategy, it is recommended that companies conduct comprehensive real-cost analyses and consider consumer preferences and multiproduct offerings, which would enable more nuanced decision-making.

Acknowledgements

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Appendix

CONSUMER ACCEPTANCE TEST

Participant #________________

Samples: Beef Steaks

Date: _______

You have been provided with a tray containing 4 coded samples. Please follow the instructions as indicated:

1. **Taste each sample**
2. **Rate each and place a check mark to indicate your choice.**
3. **Expectorate the sample in the cup provided and rinse with the water provided.**
4. **Thank you for your participation.**

Sample #	Appearance	Aroma	Flavor	Texture	Overall acceptability
Like extremely					
Like very much					
Like moderately					
Like slightly					
Neither like nor dislike					
Dislike slightly					
Dislike moderately					
Dislike very much					
Dislike extremely					

Sample #	Appearance	Aroma	Flavor	Texture	Overall acceptability
Like extremely					
Like very much					
Like moderately					
Like slightly					
Neither like nor dislike					
Dislike slightly					
Dislike moderately					
Dislike very much					
Dislike extremely					

Sample #	Appearance	Aroma	Flavor	Texture	Overall acceptability
Like extremely					
Like very much					
Like moderately					
Like slightly					
Neither like nor dislike					
Dislike slightly					
Dislike moderately					
Dislike very much					
Dislike extremely					

Sample #	Appearance	Aroma	Flavor	Texture	Overall acceptability
Like extremely					
Like very much					
Like moderately					
Like slightly					
Neither like nor dislike					
Dislike slightly					
Dislike moderately					
Dislike very much					
Dislike extremely					

Step 2: Willingness to pay auction

Beef Steak Auction Instructions

Please follow along as I read the following instructions. There is to be **no talking** between participants during the session. If you have any questions, please notify the Moderator at any time.

Thank you for agreeing to participate in today's auction session. Before we begin, we want to remind you that your participation in the auction session is completely voluntary, and the results from which will remain confidential.

Auctioning Procedures

In today's auction, we are primarily interested in your *value preferences* for beef steaks.

We will provide you with a MAFES Store Voucher which is your allowance from which you can attempt to purchase a beef steak weighing 12 ounces, which is 0.75 pounds. The starting balance on your Voucher is $21.00.

You are being asked to submit a single Bid for each type of beef steak based on the sample that you have tasted. Bids are in $ per pound. You may only place bids ranging from $0.00 to $28 per pound for each type of beef steak.

After you have submitted your Bid, the moderator will *randomly* draw which beef steak you are eligible to win and a corresponding Price per pound for the beef steak. Possible prices per pound are in 1-cent increments, ranging from $0.00 to $28.00, such that a 12-ounce beef steak with a Price per pound of $28.00 is equivalent to your $21.00 budget. Please note that you have an equal chance of being eligible for each beef steak and the corresponding Price per pound within the range of values has an equal chance of being drawn.

If the Bid you submit for your randomly drawn eligible beef steak is **greater than or equal to** the randomly drawn Price per pound, then you will win the beef steak. However, you will only be required to pay the randomly drawn Price, not your Bid. If you win, the randomly drawn Price per pound will be deducted from the initial $21.00 balance on your MAFES Store Voucher.

If the Bid you submit for your randomly drawn eligible beef steak is **less than** the randomly drawn Price per pound, you will not win the beef steak and the balance on your MAFES Store Voucher will equal the original $21.00.

Regardless of the outcome, you will leave either with, i) product and a remaining balance on the Voucher or ii) the initial Voucher amount.

Here is an Example

If you submit a Bid per pound and the randomly drawn Price per pound are:

Eligible Beef Steak	Bid	Price
#X	$12.34	$20.25
#Y	$20.50	$15.00

In case of #X, because your Bid is less than the randomly drawn Price, you will receive only the MAFES Store Voucher = $21.00.

In case of #Y, because your Bid is greater than the randomly drawn Price per pound, you will win #Y and pay a Price per pound of $15.00, not the $20.50 you Bid. For the 12-ounce steak (0.75 pounds), you will pay (0.75 * $15.00) = $11.25. Therefore, you will receive #Y and a $9.75 MAFES Store Voucher = $21.00 – $11.25.

NOTE: Because Price per pound is randomly determined, you are not competing against other bidders to win a beef steak.

Any Questions?

AUCTION EXPERIMENT

Bidding Sheet

Participant #_______________

Please refer to the information you provided on the **CONSUMER ACCEPTANCE TEST** to determine your **Value** and **Bid** for sample. Please take your time in this evaluation process.

Please do not talk with other participants while considering your Bids or let them see your Bidding Sheet.

REMINDERS:

1. Possible prices per pound are in 1 cent increments, ranging from $0.00 to $28.00. Please note that any Price within this range has an equal chance of being drawn.
2. Allowable Bids per pound are any value in 1 cent increments between $0.00 and $28.00.

If you have any questions, please notify the moderator.

Please enter the steak number and submit your Bid:

Steak #_________ Bid = $_________ per pound
Steak #_________ Bid = $_________ per pound
Steak #_________ Bid = $_________ per pound
Steak #_________ Bid = $_________ per pound

PLEASE NOTIFY THE MODERATOR WHEN YOU ARE DONE AND HE/SHE WILL CALCULATE YOUR RESULTS FROM THE AUCTION.

Please continue to the next page where you are asked to provide some demographic information. If you have any questions, please notify the moderator.

Exit Questionnaire: Participant # ________

If you have any questions, please notify the moderator if you do not understand the question.

1. If you have not had COVID-19, skip this question. If you have had COVID-19, has your current sense of taste and smell been impacted?
   a. Yes____
   b. No____
2. Prior to today, have you ever purchased beef steak?
   a. No____
   b. Yes____
   c. Unsure____
3. Prior to today, have you ever consumed beef steak?
   a. No____
   b. Yes____
   c. Unsure____
4. Who is the primary decision marker concerning meat purchases in your household?
   a. Yourself ______
   b. Spouse ______
   c. Joint decision ______
   d. Other ______
5. How much do you typically spend on beef steaks on a per pound basis at the grocery store? Or select 'unsure' if you are uncertain.
   a. $ _________
   b. Unsure ____
6. Where do you purchase meat products most often?
   a. Health/natural foods store ____
   b. Retail grocery store ____
   c. Farmers' market/local cooperative ____
   d. Directly from producer ____
   e. Internet or direct mail order ____
7. Please list your age. ________
8. What is your gender?
   a. Male ____
   b. Female ____
9. In which range does your annual before-tax household income fall?
   a. Under $20,000 ____
   b. $20,000 to $39,999 ____
   c. $40,000 to $59,999 ____
   d. $60,000 to $79,999 ____
   e. $80,000 to $99,999 ____
   f. $100,000 or more ____
10. Please identify your highest education level.
    a. High school, no degree ____
    b. High school degree or GED ____
    c. College degree (Bachelors, Associates) ____
    d. Graduate degree ____
11. Where were you raised? (If in the U.S., please list which state. If not from the U.S., then list which country) _______________
12. Have you or your family ever been involved in production agriculture?
    a. Yes____
    b. No____
13. Do you have any concerns with the beef products currently available on the market?
    a. No____
    b. Yes____
    If yes, which of the following reflect those concerns? (Check all that apply.)
    ____Health (e.g., cholesterol, fat content)
    ____Sanitation (e.g., E. Coli, Salmonella)
    ____Production of processing practices
    ____Possibility of containing antibiotics/growth hormones
    ____Environmental impacts
    ____Other:____________________________

YOU ARE NOW DONE! THANK YOU VERY MUCH.