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Brahman and Brahman crossbred cattle grown on pasture and in feedlots in subtropical and temperate Australia. 2. Meat quality and palatability

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Abstract. Market demand for a reliable supply of beef of consistently high eating quality led the Cooperative Research Centre for Cattle and Beef Industry (Meat Quality) to initiate a crossbreeding progeny test program to quantify objective and sensory meat quality differences between straightbred and first-cross Brahman cattle. Brahman, Belmont Red, Santa Gertrudis, Angus, Hereford, Shorthorn, Charolais and Limousin sires were mated to Brahman females over 3 years to produce 1346 steers and heifers in subtropical northern Australia. Calves were assigned within sire by age and weight to one of three market endpoints (domestic, Korean or Japanese), one of two finishing environments (subtropical or temperate) and one of two finishing diets (pasture or feedlot). Average carcass weights were 227, 288 and 327 kg for domestic, Korean and Japanese markets respectively. Only steers were finished for the Japanese market. The effects of sire breed, finishing regime, market endpoint and sex on sensory meat quality of four attributes score (CMQ4), ossification score and Warner-Bratzler shear force (SF), instron compression (IC), ultimate pH and percent cooking loss (CL) on the *M. longissimus thoracis et lumborum* (LT) and *M. semitendinosus* (ST) were determined. Straightbred Brahmans had the highest SFLT (5.39 $\pm$ 0.07; $P < 0.001$), ICLT (1.89 $\pm$ 0.02; $P < 0.05$) and CL in both muscles ($P < 0.05$). Straightbred Brahmans were the only genotype that failed to meet minimum CMQ4 grading standards (38.3; $P < 0.001$). Progeny with up to 75% Brahman content successfully met minimum objective and sensory meat quality consumer thresholds for tenderness (IC <2.2 kg, SF <5.0 kg; CMQ4 >46.5). There was little difference between crossbred progeny for most meat quality traits. All feedlot-finished animals were slaughtered at domestic, Korean and Japanese market weights by 24 months of age, with minimal differences in objective measures of meat quality between markets. The IC measures for all sire breeds were below 2.2 kg, indicating connective tissue toughness was not an important market consideration in feedlot-finished animals slaughtered by 24 months of age. Pasture finishing adversely affected all meat quality traits ($P < 0.001$) except CLST, with Korean and Japanese market animals having unacceptably tough SF, IC and CMQ4 measures. This was attributed to their older age at slaughter (31 and 36 months respectively), resulting from their seasonally interrupted growth path. While domestic animals slaughtered at 25 months of age off pasture had unacceptably high SF and IC, CMQ4 was acceptable. Subtropical feedlot animals had slightly more desirable (n.s.) SF and IC relative to temperate feedlot animals, whereas temperate feedlot animals had higher CMQ4 ($P < 0.001$). Genotype $\times$ environment interactions were not important.

Introduction

Beef eating quality is particularly important to Australia's premium beef markets. Domestic and Japanese consumers rate tenderness as the single most important eating quality attribute (Egan *et al*. 2001). A study by Sensory Market Analysis and Research Technology (1994) found that 77% of consumers would purchase more beef if they knew it was going to be tender. The domestic market consumes 37% of our total beef production, while Japan remains Australia's most important premium beef market. Korea is our third largest export market (Australian Bureau of Statistics 2006). Australian beef producers are under market pressure for a year-round supply of beef of consistently high eating quality.

Brahman is the predominant cattle breed in northern Australia due to its superior adaptation to the production environment. Over 50% of the national herd is estimated to have some Brahman genes (Bindon 2002). However, it is well documented that as the proportion of *Bos indicus* inheritance increases, shear force (SF) increases and marbling and sensory tenderness values decrease (Koch *et al*. 1982; Crouse *et al*. 1989; Whipple *et al*. 1990; Marshall 1994; Shackelford *et al*. 1995; Cundiff *et al*. 1998; Thompson *et al*. 1999*a*; Wheeler

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et al. 2001; Thompson 2002). While there have been many studies comparing cattle with varying proportions of *B. indicus* genes to *Bos taurus* animals in temperate environments, there are few studies comparing *B. indicus* with *B. indicus* × *B. taurus* crosses in tropical and subtropical environments. The majority of experiments conducted in subtropical environments have been in the USA and vary in the breadth of the breed combinations used and findings of the effect of *B. indicus* content on meat quality (Peacock *et al*. 1982; Wythes *et al*. 1989; Johnson *et al*. 1990; DeRouen *et al*. 1992; Pringle *et al*. 1997; Bidner *et al*. 2002). The debate on genotype × environment interactions on meat quality remains controversial. In extreme environments, poor adaptation is believed to be responsible for changes in breed rankings for meat tenderness. A study by Pratchett *et al*. (1988) in the arid tropics of northern Australia of 2.5- and 3.5-year-old cattle averaging 193.7 and 249.8 kg, respectively, found Shorthorns did not differ significantly from Brahman × Shorthorn crosses for SF (5.24 kg *v*. 5.26 kg respectively), and Africander × Shorthorn (4.51 kg) had the most tender beef. The study also found no significant difference in tenderness scores between Shorthorn, Brahman and Brahman × Shorthorn crosses.

In 1994 the Cooperative Research Centre for Cattle and Beef Industry (Meat Quality) (Beef CRC) initiated its Northern Crossbreeding Program. The primary objective of this experiment was to identify differences between straightbred Brahmans and Brahman crossbreds for beef eating quality when finished on pasture and grain in subtropical and temperate environments to the specifications of Australia's three main premium beef markets. Of particular interest was whether existing national cattle breeding programs were suitable to deliver the most efficient animals for pasture- and feedlot-finishing systems, or whether there was a need to develop a separate breeding strategy for the feedlot sector (Bindon 2001). Meat Standards Australia (MSA) used all animals generated for the Crossbreeding Program to underpin and further develop their beef grading scheme. The MSA beef grading scheme was launched in 1997 with the primary aim of providing a guarantee of eating quality to the consumer (Polkinghorne *et al*. 1999). While genetic correlations between objective measures of tenderness and sensory tenderness are high and negative, the phenotypic correlations are low (Reverter *et al*. 2003). Therefore, untrained consumer taste panels were used in setting the MSA palatability grades. A pilot program conducted by MSA in 1998 demonstrated a high repurchase rate by consumers if they were presented with a product that was graded consistently (Thompson *et al*. 1999*b*). Preliminary analysis of objective meat quality traits were reported by Newman *et al*. (1999). This paper presents the full report on the effects of sire breed, finishing regime, market endpoint and sex on sensory and objective meat quality characteristics of crossbred Brahman progeny from the Northern Crossbreeding Program.

Materials and methods

Experimental design and animals

Full details of experimental design, measurements and data storage were described by Upton *et al*. (2001). Briefly, calves by 1000 Brahman dams and eight terminal sire breeds were bred over 3 years in subtropical central Queensland on 'Duckponds' and Brigalow Research Station. Sire breeds represented *B. indicus* (Brahman – purebred control), *B. indicus* × British-derived (Santa Gertrudis), *B. taurus* × Sanga-derived (Belmont Red), *B. taurus* – British (Angus, Hereford, Shorthorn), and *B. taurus* – Continental (Charolais, Limousin). Brahman, Santa Gertrudis and Belmont Red are tropically adapted breeds. Calves were generated by natural mating and artificial insemination (AI). Most British sires were used by AI because the bulls were located in southern Australia. A full description of AI programs and parentage determination is given by Corbet *et al*. (1997, 1999). The aim was to produce ~10 steers and 10 heifers per sire. The optimal number of sires, offspring per sire and number of link sires between herds, and allocation of animals to treatment combinations are discussed by Robinson (1995). All male calves were castrated at ~4 months of age. Meat quality measurements were recorded for 1346 steers and heifers. Table 1 shows the number of sires and progeny measured per breed.

Treatments

Calves were weaned in 1996, 1997 and 1998 at about 6 months of age. Calves were assigned within sire by age and weight to one of three market endpoints (domestic, Korean or Japanese), one of two finishing environments (subtropical or temperate) and one of two finishing diets (pasture or feedlot). The finishing treatments are combined and identified as subtropical pasture, subtropical feedlot and temperate feedlot throughout the manuscript. No animals were finished on pasture in the temperate environment. Following weaning two-thirds of the calves were grown out in the subtropics on buffel grass (*Cenchrus ciliaris*) pasture at 'Duckponds'. The remaining one-third of the calves were grown out in temperate New South Wales on pasture at Glen Innes Research Station (refer to Ayres *et al*. 2001 for native and improved pasture descriptions) or 'Tullimba' (native wallaby grass, *Austrodanthonia* spp.) until they reached feedlot entry weights. Calves allocated to the domestic market entered feedlots when they reached 300 kg liveweight, whereas Korean and Japanese market calves entered feedlots at 400 kg liveweight. Calves were finished on buffel grass pasture at 'Duckponds' (subtropical pasture), 'Goonoo' feedlot (subtropical feedlot) or 'Tullimba' feedlot (temperate feedlot) to estimated carcass weights of 220, 280 and 330 kg for the domestic, Korean and Japanese markets respectively. Only steers were finished to Japanese market weights. Domestic animals were grain fed for

Table 1. Number of sires and progeny per breed

Sire breed	No. of sires	Heifer progeny	Steer progeny	Total
Brahman	14	125	107	232
Belmont Red	14	125	154	279
Santa Gertrudis	8	65	44	109
Angus	10	55	63	118
Hereford	8	59	46	105
Shorthorn	8	48	41	89
Charolais	15	95	91	186
Limousin	14	118	110	228
Total	91	690	656	1346

an average of 60 days and export animals were grain fed for a minimum of 90 days (Upton *et al*. 2001).

A cohort was defined by the variables sex, year of birth, market endpoint and finishing regime. All animals within a cohort were managed as a single group during grow-out, finish, pre-slaughter and slaughter, with the exception of a few cohorts that were slaughtered over 2 consecutive days. All animals within a cohort were slaughtered when the average weight of their group reached estimated target carcass weights. One-half of all steers finished in the subtropics were repeatedly implanted with 20 mg oestradiol-17β (Compudose 100, Elanco Animal Health, Macquarie Park, NSW, Australia), a hormonal growth promotant (HGP), from ~15 months of age to slaughter. The numbers of implants given to feedlot-finished steers were one, three and four for domestic, Korean and Japanese markets respectively. The numbers of implants given to pasture-finished steers were two, five and seven for domestic, Korean and Japanese markets respectively. Experimental details and results for the HGP experiment are reported by Hunter *et al*. (2001).

Slaughter protocols and meat quality measurements

Full details of slaughter, electrical stimulation, chiller measurements, sample removal and yield measurements are reported by Perry *et al*. (2001). Best practice pre- and post-slaughter procedures were used. The aims of best practice carcass processing are to minimise myofibrillar shortening by optimising the rate of glycolysis and temperature decline, and to maximise the extent of proteolysis, while ensuring microbiological standards are met (Ferguson *et al*. 2001). Animals were stunned using a captive bolt pistol and bled immediately. Electrical stimulation was applied to all carcasses to prevent cold shortening. Depending on the abattoir, either low voltage stimulation was applied for 40 s within 5 min of stunning, or high voltage stimulation was applied to dressed sides 40–60 min after stunning (Perry *et al*. 2001).

Carcasses were dressed to comply with AUS-MEAT standard specifications (AUS-MEAT 1998). Carcasses were placed in chillers within 1 h of slaughter and hung by the Achilles tendon. The MSA assessors measured the United States Department of Agriculture ossification score (OSSIF). The left side of each carcass was quartered 20–24 h after slaughter, and the entire *M. semitendinosus* (ST) and ~15 cm of the *M. longissimus thoracis et lumborum* (LT) were removed for objective measurements of meat quality. Samples were trimmed, weighed and packed in plastic for freezing at –20°C within 36 h of slaughter (Perry *et al*. 2001). Because of the large number of samples being processed, two laboratories using standardised equipment and protocols were used (Perry *et al*. 2001). Both muscles were measured using Warner-Bratzler SF and instron compression (IC). SF is believed to reflect both myofibrillar and connective tissue components of toughness (Harris and Shorthose 1988; Harper 1999). IC mainly reflects the connective tissue toughness of muscle (Harper 1999). The ST is believed to be closer to the median value for all muscles in the carcass (Shorthose and Harris 1991).

Not every animal was measured for every trait. Slaughter operations moved to six different abattoirs in two states during the Crossbreeding Program due to abattoir closure or the inability of the abattoir to accommodate the demands and disruptions of experimental requirements in commercial meat processing plants. Consequently, some precision and considerable revenue was lost (Bindon 2001). This ultimately impacted on the completeness of the Crossbreeding Program dataset. OSSIF and clipped meat quality four attributes score (CMQ4; refer to Table 2) were only measured on the 1996 and 1997 calf crops. Consequently, there were no domestic steers or domestic heifers

Table 2. Abbreviations and definitions of meat quality traits

Abbreviation	Definition of traits
SFLT (kg)	Warner-Bratzler shear force of the *M. longissimus thoracis et lumborum*. Meat below 5.0 kg is considered tender
SFST (kg)	Warner-Bratzler shear force of the *M. semitendinosus*. Meat below 5.0 kg is considered tender
ICLT (kg)	Instron compression of the *M. longissimus thoracis et lumborum*. Meat below 2.2 kg is considered tender
ICST (kg)	Instron compression of the *M. semitendinosus*. Meat below 2.2 kg is considered tender
CLLT (%)	Cooking loss percent of the *M. longissimus thoracis et lumborum*. Samples were weighed (pre-cook weight) and placed in individual bags in a preheated water bath at 70°C for 60 min, then cooled in cold running tap water for 30 min. Cooked samples were removed from bags, dried and weighed to determine a post-cook weight. Cooking loss was determined as the percentage difference between pre- and post-cooked weights (refer to Perry *et al*. 2001 for full details)
CLST (%)	Cooking loss percent of the *M. semitendinosus*. Samples were prepared as per CLLT
PHLT (pH)	Ultimate pH of the *M. longissimus thoracis et lumborum*. Four measures of pH were taken per sample using a digital pH meter with a combination electrode, and averaged to provide a measure of ultimate pH. The acceptable range for pH is 5.3–5.7. A slight improvement in eating quality occurs as pH declines from 5.7 to 5.4
PHST (pH)	Ultimate pH of the *M. semitendinosus*. Samples were measured as per PHLT
CMQ4	Meat Standards Australia clipped meat quality score of four attributes. *M. longissimus thoracis et lumborum* samples were aged at 1°C for 14 days, the epimysium removed, steaks cut at 25 mm thickness and served grilled to a medium degree of doneness. Consumers were recruited from the community to represent diverse backgrounds and areas, were 20–50 years of age and ate beef at least once per week. Ten consumers tasted each individual cut. Each component of the score was calculated on a 0–100 scale comprising: tenderness 40%, juiciness 10%, flavour 20% and overall liking 30%. The lowest and highest two scores were 'clipped', and the middle six scores averaged to produce the CMQ4 for analysis (Polkinghorne *et al*. 1999; Perry *et al*. 2001)
OSSIF	United States Department of Agriculture ossification score. Ossification measures the physiological maturity of the carcass and gives an indication of collagen fibre development. Ossification increases as an animal ages but can also increase with nutritional or health stress. It is measured on a scale of 0–500, with higher scores indicating greater maturity and poorer eating quality. Animals fed under optimal conditions could be expected to have ossification scores of 170 and 200 at 24 and 30 months of age respectively (MLA 2003)

analysed for temperate feedlot, affecting results for effects of market endpoint, finishing regime and sex within market for CMQ4 and OSSIF. The effect of these missing cells is discussed in the relevant results.

Statistical analyses

Least squares means for fixed effects were estimated using the GLM procedure of SAS (SAS 2000). Partial confounding of fixed effects and kill groups and missing subclasses prevented convergence in the initial fixed effects model. Subsequently, each independent variable (breed, finish, market, sex, year of birth, herd of origin, HGP treatment) was fitted separately in a fixed effects model, and a second independent variable accounting for all remaining fixed effects (concatenated into one variable) was included. Sire within breed was fitted as a random effect in the breed analysis and was also used as the error term to test breed differences. The models ignored abattoir and slaughter day effects because slaughter day was completely nested within market weight and finishing regime. Abattoir was confounded within finishing environment (subtropical, temperate). Electrical stimulation method was also excluded from the model due to confounding within abattoir. Carcasses believed not to have been effectively stimulated or to have undergone cold or heat shortening were removed from the dataset (Johnston *et al*. 2001). The models used to analyse the meat quality traits are described fully in the first paper in this series (Schutt *et al*. 2009). For example, the model used to analyse the effect of sire breed on all meat quality traits was:

$$y_{ijkl} = \mu + \text{breed}_j + \text{otherFE}_k + \text{sire}_{l(j)} + b_1\text{CWT}_{ijkl} + \varepsilon_{ijkl} \quad (1)$$

where y_{ijkl} is the observation for a dependent variable for animal i, μ is the overall mean, breed_j is the effect of the jth sire breed, otherFE_k is the effect of the kth group that accounts for all other fixed effects concatenated into one variable (sex || market || finish || year of birth || herd of origin || HGP treatment), $\text{sire}_{l(j)}$ is the random effect of the lth sire nested within the jth breed, CWT_{ijkl} is the linear effect of carcass weight of the animal fitted as a covariate, and ε_{ijkl} is the residual error term.

Least squares means were estimated for two-way interactions between all fixed effects. Of particular interest were breed × finish, breed × market and market × finish interactions. Interactions were calculated using a concatenated fixed effects model using the GLM procedure of SAS (SAS 2000). For example, breed × market interaction was tested using:

$$y_{ijkl} = \mu + \text{breed}_j + \text{market}_k + \text{otherFE}_l + (\text{breed} * \text{market})_{jk} + b_1\text{CWT}_{ikl(k)} + \varepsilon_{ijkl} \quad (2)$$

where y_{ijkl} is the observation for a dependent variable for animal i, μ is the overall mean, breed_j is the effect of the jth sire breed, market_k is the effect of the kth market endpoint, otherFE_l is the effect of the lth group that accounts for all other fixed effects concatenated into one variable (sex || finish || year of birth || herd of origin || HGP treatment), $b_1\text{CWT}_{ikl(k)}$ is the linear effect of carcass weight of the animal fitted as a covariate within market, and ε_{ijkl} is the random residual error.

The multiple range test devised by Duncan (1955) and extended by Kramer (1957) was used to test for significant differences between means.

All meat quality traits were adjusted to a common hot carcass weight for breed and finish effects, and a common hot carcass weight within market endpoint for market and sex within market effects. Steers implanted with HGP were excluded from analyses for finish and sex effects due to confounding with location and sex. Subsequently, only 1136 animals were analysed for finish and sex effects for SFLT (SF of the LT muscle), ICLT (IC of the LT), PHLT (ultimate pH of the LT), CLLT (percent cooking loss of the LT), SFST (SF of the ST muscle), ICST (IC of the ST), PHST (ultimate pH of the ST) and CLST (CL of the ST), and 460 animals for CMQ4 and OSSIF. Traits reported in this paper are described in Table 2.

Results

Least squares means for age at slaughter and unadjusted hot carcass weight for sire breed, finishing regime, market endpoint and sex within market effects are reported in the first paper in this series (Schutt *et al*. 2009).

Sire breed effects

Tables 3 and 4 show least squares means for the effect of sire breed on objective and sensory meat quality traits of animals across all markets and finishing regimes. Higher SF and IC values indicate less tender meat. Australian consumers would rate meat with SF of less than 5.0 kg as tender (Egan 1997) and IC measures of less than 2.2 kg as tender (Gazzola 1997). Given all breeds had IC measures of the LT and ST below 2.2 kg, and breeds did not differ significantly for ICST, connective tissue toughness did not appear to be an important market consideration in this experiment where animals were slaughtered at an average age of 24 months. Overall, there was little difference between genotypes for objective measures of meat quality. Straightbred Brahmans had the toughest LT meat quality (refer to Table 3), but did not differ significantly from Shorthorn sired crosses for SFLT, or Santa Gertrudis and Hereford sired crosses for CLLT. Angus sired progeny had the most desirable LT meat quality, but were not significantly different to all other crossbreds except Shorthorn crosses and straightbred Brahmans for SFLT ($P < 0.001$), and Santa Gertrudis crosses and straightbred Brahmans for CLLT ($P < 0.05$). Angus and Shorthorn crossbreds had the toughest SFST, differing significantly ($P < 0.001$) from Charolais and Limousin crosses. Hereford and Shorthorn sired progeny had the lowest CLST but only differed significantly ($P < 0.05$) to straightbred Brahmans. All breeds fell within the acceptable range of 5.3–5.7 for ultimate pH (Ferguson *et al*. 2001). There was no significant difference in OSSIF between breeds.

Straightbred Brahmans did not differ significantly from Belmont Red or Santa Gertrudis sired progeny for most LT and ST meat quality traits. The exceptions were: Brahmans differed significantly ($P < 0.001$) to Belmont Red and Santa

Table 3. Least squares means (±s.e.) for effect of sire breed on objective measures of meat quality on the *M. longissimus thoracis et lumborum* and *M. semitendinosus* in steers and heifers

See Table 2 for abbreviations and definitions of meat quality traits. Traits are adjusted to a common hot carcass weight. n.s., not significant

Sire breed	No. of animals	SFLT (kg)	ICLT (kg)	PHLT (pH)	CLLT (%)	SFST (kg)	ICST (kg)	PHST (pH)	CLST (%)
Brahman	232	5.39 ± 0.07	1.89 ± 0.02	5.53 ± 0.01	23.4 ± 0.1	5.01 ± 0.04	2.11 ± 0.02	5.57 ± 0.01	24.3 ± 0.1
Belmont Red	279	5.00 ± 0.06	1.85 ± 0.02	5.52 ± 0.01	22.8 ± 0.1	4.95 ± 0.04	2.14 ± 0.02	5.55 ± 0.01	23.6 ± 0.1
Santa Gertrudis	109	4.95 ± 0.11	1.87 ± 0.03	5.53 ± 0.01	23.2 ± 0.2	4.89 ± 0.07	2.07 ± 0.04	5.55 ± 0.01	23.9 ± 0.2
Angus	118	4.68 ± 0.09	1.78 ± 0.02	5.54 ± 0.01	22.6 ± 0.2	5.07 ± 0.05	2.10 ± 0.03	5.55 ± 0.01	23.8 ± 0.2
Hereford	105	4.80 ± 0.09	1.78 ± 0.02	5.53 ± 0.01	22.9 ± 0.2	4.97 ± 0.05	2.10 ± 0.03	5.56 ± 0.01	23.4 ± 0.2
Shorthorn	89	5.05 ± 0.10	1.87 ± 0.03	5.54 ± 0.01	22.7 ± 0.2	5.08 ± 0.06	2.15 ± 0.03	5.56 ± 0.01	23.4 ± 0.2
Charolais	186	4.90 ± 0.09	1.83 ± 0.02	5.53 ± 0.01	22.7 ± 0.2	4.81 ± 0.06	2.17 ± 0.03	5.56 ± 0.01	23.9 ± 0.2
Limousin	228	4.80 ± 0.07	1.79 ± 0.02	5.54 ± 0.01	22.6 ± 0.1	4.65 ± 0.04	2.07 ± 0.02	5.57 ± 0.01	23.8 ± 0.1
l.s.d. (P = 0.05)	–	0.36	0.10	0.03	0.6	0.23	0.13	0.03	0.6
	1346	P < 0.001	P < 0.05	n.s.	P < 0.05	P < 0.001	n.s.	n.s.	P < 0.05

Table 4. Least squares means (±s.e.) for effect of sire breed on Meat Standards Australia clipped meat quality of four attributes score (CMQ4) and ossification score (OSSIF) for steers and heifers

Traits are adjusted to a common hot carcass weight. n.s., not significant

Sire breed	No. of animals	CMQ4 (out of 100)	OSSIF
Brahman	103	38.3 ± 1.4	175 ± 4
Belmont Red	139	50.4 ± 1.1	176 ± 3
Santa Gertrudis	56	48.8 ± 2.1	167 ± 5
Angus	46	53.8 ± 2.0	184 ± 5
Hereford	47	49.9 ± 1.9	177 ± 5
Shorthorn	37	48.4 ± 2.3	176 ± 6
Charolais	50	51.8 ± 2.1	182 ± 6
Limousin	99	49.9 ± 1.4	173 ± 4
l.s.d. (P = 0.05)	–	7.4	19
	577	P < 0.001	n.s.

Gertrudis crosses for SFLT, and Brahmans differed significantly (P < 0.05) to Belmont Red crosses for CLLT and CLST.

Straightbred Brahmans differed significantly (P < 0.001) to all crossbred genotypes for CMQ4. Angus sired progeny had the most desirable CMQ4 but were not significantly different to all other crossbreds. Straightbred Brahmans failed to meet the MSA 3-star grading cut-off point of 46.5, shown in Fig. 1. Despite a CMQ4 least squares mean of 38.3, 29% of the Brahmans graded 3-star or better, and 6% graded 4-star. Analyses of sex within breed showed 42% of Brahman steers and 27% of Brahman heifers graded 3-star or better. Table 5 shows the percentage of progeny by each sire breed that failed to achieve MSA grading standards based on CMQ4. Belmont Red and Santa Gertrudis sired crosses were the only genotypes to achieve MSA 5-star grading (CMQ4 >79 out of 100).

Pasture v. *feedlot finishing*

Significant differences between pasture and feedlot finishing were found for all meat quality traits (P < 0.001). Tables 6 and 7 show the effect of finishing regime on objective and sensory meat quality traits across all market endpoints. Animals finished on subtropical pasture averaged 7 months older (28 *v.* 21 months) and had significantly higher OSSIF than subtropical feedlot-finished animals. Meat from pasture-finished animals was above acceptable consumer tenderness thresholds for SFLT, SFST and ICST (SF greater than 5.0 kg and IC greater than 2.2 kg; Egan 1997; Gazzola 1997). Fig. 2 shows finishing regime effects on (*a*) SFLT and (*b*) ICST at each market endpoint, and clearly demonstrates the negative impact of pasture finishing on meat quality. Despite less than 3 months difference in age at slaughter, pasture-finished domestic animals (averaging 751 days) had significantly higher (P < 0.001) SFLT and ICST measures than feedlot-finished Korean and Japanese market animals (averaging 687 and 715 days respectively), which suggests factors other than age affect meat quality. Ultimate pH was significantly higher for the LT and ST muscles of pasture-finished animals, though all measures of pH were within the acceptable range of 5.3–5.7 (Ferguson *et al*. 2001). Although CLLT was significantly higher for pasture-finished animals relative to their feedlot-finished contemporaries, the opposite trend occurred for CLST.

CMQ4 were consistent with objective meat quality measures. Except for Angus crossbreds, pasture-finished animals were unable to achieve minimum MSA grading standards (CMQ4 > 46.5). However, there was a sex effect on sensory meat quality scores. With the exception of Angus sired crosses, no pasture-finished heifers met minimum MSA grading standards. Brahman, Charolais, Santa Gertrudis and Shorthorn sired steers also failed to grade MSA when finished on pasture (results not shown). The adverse effect of pasture finishing on sensory meat quality (CMQ4) is shown in Fig. 1.

Subtropical v. *temperate finishing environments*

There were no significant differences between feedlots for SFLT, ICLT and SFST averaged across market endpoints. Ultimate pH was lower (P < 0.001) in LT and ST muscles from temperate feedlot animals relative to subtropical feedlot animals, though all pH values were within the acceptable range. The SF and IC measures of both muscles were within the limits associated with acceptable tenderness (5.0 and 2.2 kg

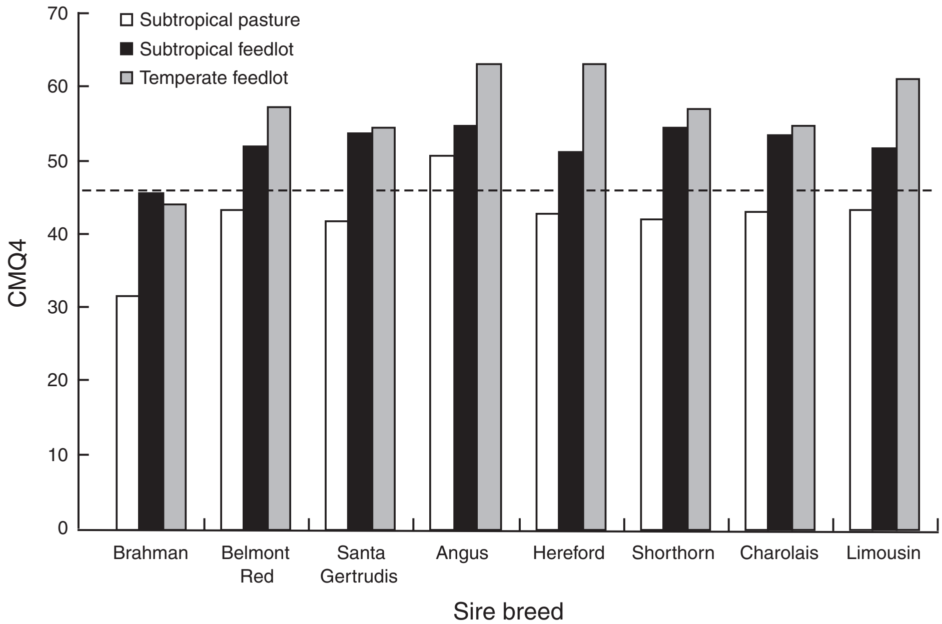

Fig. 1. Finishing regime effect on Meat Standards Australia (MSA) clipped meat quality of four attributes score (CMQ4) for each sire breed ($n = 460$). The line at CMQ4 46.5 indicates the minimum score for MSA 3-star grading.

Table 5. Percentage of sire breeds to grade Meat Standards Australia 3-star, 4-star and 5-star based on clipped meat quality of four attributes score (CMQ4)

Sire breed	No. of animals	Fail (CMQ4 <46.5) (%)	3-star (CMQ4 46.5–64) (%)	4-star (CMQ4 64–79) (%)	5-star (CMQ4 79+) (%)
Brahman	103	65.1	29.1	5.8	–
Belmont Red	139	40.3	44.6	13.7	1.4
Santa Gertrudis	56	48.2	39.3	10.7	1.8
Angus	46	32.6	50.0	17.4	–
Hereford	47	44.7	38.3	17.0	–
Shorthorn	37	46.0	37.8	16.2	–
Charolais	50	50.0	44.0	6.0	–
Limousin	99	50.5	36.4	13.1	–
Total	577	48.2	39.3	12.1	0.4

respectively; Egan 1997; Gazzola 1997). Export market animals finished in the temperate feedlot had significantly higher ($P < 0.001$) ICST than their subtropical feedlot contemporaries, but also had higher ($P < 0.001$) CMQ4 (refer to Fig. 3) than subtropical feedlot animals. Animals from both feedlot environments achieved minimum MSA grading standards.

While pre- and post-slaughter protocols and laboratory analyses of meat quality were controlled as closely as possible (refer to Perry *et al*. 2001) it is unquestionable that differences in the pre-slaughter treatment of animals and processing of meat products occurred between different locations. Consequently, significant differences in meat quality between subtropical feedlot and temperate feedlot-finished cattle may include differences due to other confounded variables within the finishing regimes (abattoir, slaughter day, electrical stimulation, laboratory).

Market endpoint effects

Market endpoint demonstrated the effect of age on meat quality. Tables 6 and 7 show meat quality results for domestic, Korean and Japanese market animals finished on pasture and in feedlots. Mean age at slaughter was 643 ± 4, 761 ± 2 and 817 ± 6 days for the respective markets. As animals aged from domestic to Korean weights, significant increases were found for ICLT, PHLT, SFST, ICST, PHST, CLST and OSSIF (refer to Tables 6 and 7). Connective tissue toughness was below the 2.2 kg compression threshold (Gazzola 1997) for these animals, but ICST was nearing the point of unacceptable limits for export market animals, suggesting connective tissue toughness was becoming an issue for animals greater than 761 days (25 months) of age. The SF measures showed myofibrillar toughness was also becoming an issue for Japanese animals by 817 days (27 months of age). Yet they had more desirable CMQ4 (n.s.) relative to younger market animals. This was possibly due to a sex effect as heifers were absent from the Japanese market. Korean and Japanese market animals only differed significantly for PHLT, but all markets were within the acceptable ultimate pH range. Despite 56 days difference in age at slaughter, Korean animals had slightly higher OSSIF (n.s.) than Japanese animals. This was most likely a result of heifers taking 46 days longer than steers to finish to Korean weights and their faster rate of physiological maturity relative to steers.

Table 6. Least squares means (±s.e.) for effect of finishing regime, market endpoint and sex within market on objective measures of meat quality in steers and heifers

See Table 2 for abbreviations and definitions of meat quality traits. Traits are adjusted to a common hot carcass weight for finishing regime, and a common hot carcass weight within market endpoint for market and sex effects Finishing regime and sex within market effects exclude steers treated with hormonal growth promotant. Japanese market – steers only. n.s., not significant

Fixed effects	No. of animals	SFLT (kg)	ICLT (kg)	PHLT (pH)	CLLT (%)	SFST (kg)	ICST (kg)	PHST (pH)	CLST (%)
Finishing regime									
Subtropical pasture	294	5.45 ± 0.06	1.96 ± 0.02	5.57 ± 0.01	23.6 ± 0.1	5.12 ± 0.04	2.30 ± 0.02	5.60 ± 0.01	23.2 ± 0.1
Subtropical feedlot	355	4.63 ± 0.05	1.70 ± 0.01	5.53 ± 0.01	21.9 ± 0.1	4.90 ± 0.03	1.94 ± 0.02	5.55 ± 0.01	23.8 ± 0.1
Temperate feedlot[A]	487	4.69 ± 0.05	1.75 ± 0.01	5.46 ± 0.01	22.9 ± 0.1	4.81 ± 0.03	2.01 ± 0.02	5.51 ± 0.01	23.4 ± 0.1
l.s.d. (P = 0.05)		0.18	0.06	0.03	0.3	0.12	0.06	0.03	0.3
	1136	$P < 0.001$	$P < 0.001$	$P < 0.001$	$P < 0.001$	$P < 0.001$	$P < 0.001$	$P < 0.001$	$P < 0.001$
Market endpoint									
Domestic[A]	445	5.03 ± 0.09	1.73 ± 0.02	5.48 ± 0.01	22.4 ± 0.2	4.76 ± 0.06	2.02 ± 0.03	5.50 ± 0.01	22.8 ± 0.2
Korean	668	5.01 ± 0.05	1.87 ± 0.01	5.55 ± 0.01	22.8 ± 0.1	5.03 ± 0.03	2.18 ± 0.02	5.57 ± 0.01	24.1 ± 0.1
Japanese	233	5.17 ± 0.13	1.86 ± 0.04	5.50 ± 0.01	23.1 ± 0.3	5.24 ± 0.09	2.13 ± 0.05	5.57 ± 0.01	23.4 ± 0.3
l.s.d. (P = 0.05)		0.38	0.12	0.03	0.9	0.26	0.15	0.03	0.9
	1346	n.s.	$P < 0.05$	$P < 0.05$	n.s.	$P < 0.05$	$P < 0.05$	$P < 0.05$	$P < 0.05$
Sex (market)									
Domestic heifers[A]	240	4.94 ± 0.10	1.71 ± 0.03	5.50 ± 0.01	22.1 ± 0.2	4.90 ± 0.06	2.11 ± 0.04	5.51 ± 0.01	22.6 ± 0.2
Domestic steers[A]	120	5.04 ± 0.11	1.68 ± 0.03	5.45 ± 0.01	22.9 ± 0.2	4.72 ± 0.07	1.94 ± 0.04	5.48 ± 0.01	22.6 ± 0.2
Korean heifers	450	5.01 ± 0.05	1.80 ± 0.01	5.54 ± 0.01	22.6 ± 0.1	5.11 ± 0.03	2.20 ± 0.02	5.56 ± 0.01	23.6 ± 0.1
Korean steers	162	4.72 ± 0.08	1.88 ± 0.02	5.56 ± 0.01	23.0 ± 0.1	4.92 ± 0.05	2.14 ± 0.03	5.60 ± 0.01	24.3 ± 0.2
Japanese steers	164	4.89 ± 0.12	1.83 ± 0.03	5.47 ± 0.01	23.3 ± 0.2	4.97 ± 0.08	2.02 ± 0.04	5.58 ± 0.01	23.2 ± 0.2
l.s.d. (P = 0.05)		0.37	0.09	0.03	0.6	0.25	0.12	0.03	0.6
	1136	n.s.	$P < 0.05$	$P < 0.001$	$P < 0.001$	n.s.	$P < 0.001$	$P < 0.001$	$P < 0.001$

[A]No domestic animals were finished in the temperate feedlot.

Sex effects

Heifers and steers were managed separately following weaning, so direct comparisons are not possible. Nevertheless, results in Tables 6 and 7 show some interesting trends. There was little difference between the sexes for SFLT, SFST, ICLT and ICST, though domestic heifers had higher ($P < 0.001$) ICST relative to domestic steers, and heifers had higher ($P < 0.001$) OSSIF than steers at domestic and Korean weights. Significant differences in OSSIF between the sexes may be explained by differences in age at slaughter ($P < 0.001$; refer to Schutt *et al.* 2009) and the faster rate of physiological maturity of heifers relative to steers at common weights. This was also reflected in poorer ($P < 0.001$) CMQ4 for domestic heifers relative to domestic steers.

Herd of origin effects

Herd of origin had little effect on meat quality. The exceptions were SFLT being 5.05 ± 0.03 and 4.83 ± 0.05 for animals bred at 'Duckponds' and Brigalow Research Station, respectively ($P < 0.001$), and CLLT was 0.26% higher ($P < 0.05$) for the Brigalow Research Station animals.

Year effects

Year of birth was significant for most meat quality traits. ICST, CLST, PHLT, PHST and CMQ4 were highest in 1996. In 1998, SFST was highest and ICLT was lowest ($P < 0.001$).

Interactions

Most significant interactions were a result of scale effects rather than re-ranking of sire breeds for meat quality traits. The significant breed × finish interaction ($P < 0.05$) for ICST across markets showed all sire breeds had slightly higher ICST in the temperate feedlot relative to the subtropical feedlot, except Limousin sired crosses. Similarly, the breed × finish interaction ($P < 0.05$) for ICLT showed a change in ranking of Angus and Shorthorn sire breeds between feedlot-finishing regimes. However, all sire breeds finished in feedlots had ICST and ICLT lower than the 2.2 kg compression threshold considered tender by consumers (Gazzola 1997). A significant breed × market interaction ($P < 0.05$) for SFST showed a change in ranking of British type breeds for this trait.

Market × finish interactions were significant ($P < 0.05$) for all meat quality traits examined. The market × finish interaction ($P < 0.05$) for CMQ4 showed Japanese animals had poorer eating quality than Korean animals when finished on pasture, while the opposite was true for both feedlot-finishing regimes. This was likely due to the older age at slaughter of Japanese animals finished on pasture relative to feedlot finishing (36 *v.* 23 months for pasture *v.* feedlot respectively). Even at 25 months of age, domestic animals finished on pasture failed to produce SF and IC measures within acceptably tender limits (SF less than 5.0 kg and IC less than 2.2 kg), though CMQ4 was above the acceptable threshold for consumers of 46.5.

Finish × year of birth interactions were significant ($P < 0.001$) for all meat quality traits.

Table 7. Least squares means (±s.e.) for effect of finishing regime, market endpoint and sex within market on Meat Standards Australia clipped meat quality of four attributes score (CMQ4) and ossification score (OSSIF) for steers and heifers

Traits adjusted to a common hot carcass weight for finishing regime, and a common hot carcass weight within market endpoint for market and sex effects Finishing regime and sex within market effects exclude steers treated with hormonal growth promotant. Japanese market – steers only. n.s., not significant

Fixed effects	No. of animals	CMQ4 (out of 100)	OSSIF
		Finishing regime	
Subtropical pasture	172	42.7 ± 1.1	224 ± 4
Subtropical feedlot	156	52.4 ± 1.0	147 ± 3
Temperate feedlot[A]	132	57.4 ± 1.3	126 ± 4
l.s.d. (P = 0.05)		3.8	12
	460	$P < 0.001$	$P < 0.001$
		Market endpoint	
Domestic[A]	153	46.0 ± 2.4	159 ± 8
Korean	315	47.5 ± 0.9	196 ± 3
Japanese	109	48.4 ± 2.9	192 ± 10
l.s.d. (P = 0.05)		8.5	29
	577	n.s.	$P < 0.001$
		Sex (market)	
Domestic heifers[A]	84	43.0 ± 2.6	176 ± 9
Domestic steers[A]	35	52.4 ± 2.7	141 ± 9
Korean heifers	185	46.8 ± 1.0	217 ± 3
Korean steers	85	51.1 ± 1.5	171 ± 5
Japanese steers	71	54.8 ± 2.4	155 ± 8
l.s.d. (P = 0.05)	–	8.3	28
	460	$P < 0.001$	$P < 0.001$

[A]No domestic animals were finished in the temperate feedlot.

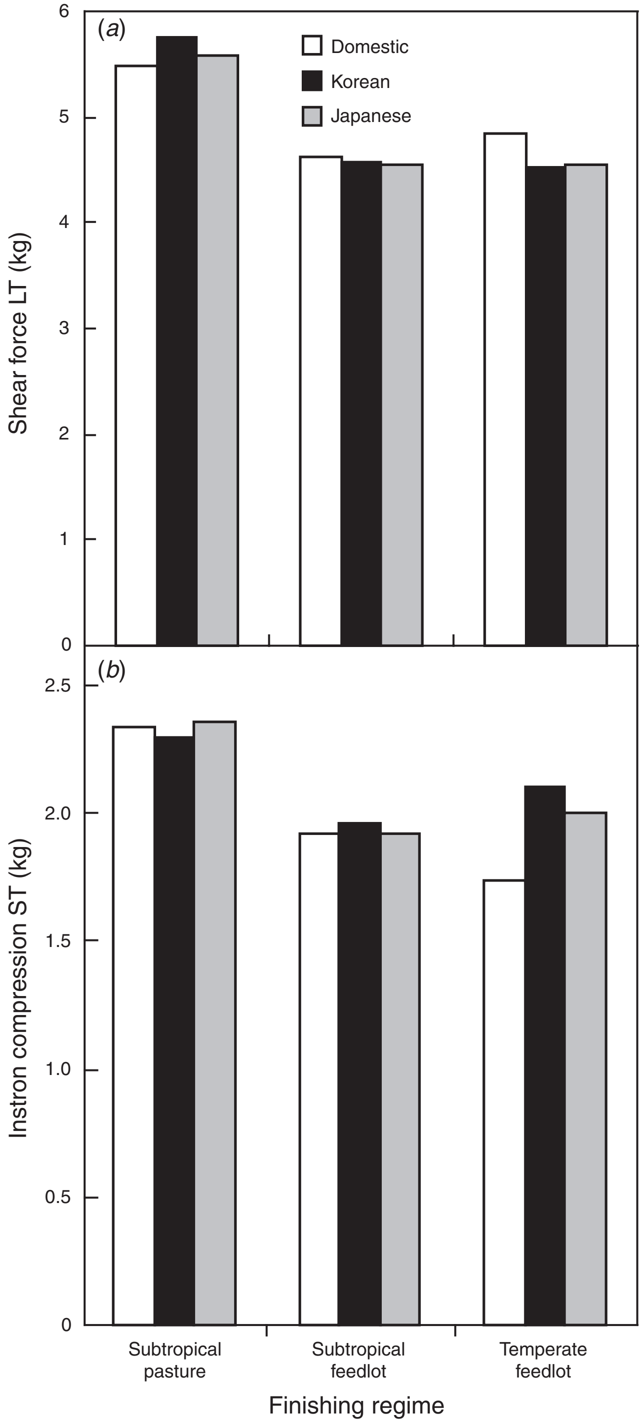

Fig. 2. Effect of finishing regime on (*a*) shear force of the *M. longissimus thoracis et lumborum* and (*b*) instron compression of the *M. semitendinosus* at three market endpoints (n = 1136).

Discussion

Sire breed effects

Schutt *et al*. (2009) reported large differences between straightbred Brahmans and Brahman crossbreds for carcass quality traits; however, there was little difference between sire breeds for most objective and sensory meat quality traits with the exception of straightbred Brahmans for sensory and LT meat quality. There was little evidence of important breed × finish and breed × market interactions on meat quality. Our results agreed with other meat quality studies conducted in subtropical environments. Two feedlot-finishing studies in the USA (Peacock *et al*. 1982; DeRouen *et al*. 1992) and a pasture-based study in the Australian arid tropics (Pratchett *et al*. 1988) reported Brahman breed effects were significantly unfavourable for SF relative to Brahman × *B. taurus* crosses. However, these studies reported SF measures on Brahmans and Brahman crosses (including Brahman × Angus, Brahman × Charolais, Brahman × Hereford and Brahman × Shorthorn) that would be considered unacceptably tough (greater than 5.0 kg) for all respective genotypes, which is different to our findings. This may be due to abattoir slaughter protocols in these other studies being inconsistent with best practice pre- and post-slaughter protocols implemented in Australian abattoirs in more recent times, which reduce the negative effects of processing on meat toughness. The magnitude of the results for PHLT, SFST, ICST, PHST, CLST and CMQ4 were generally consistent with objective and sensory meat quality findings for tropically adapted straightbreds (Brahman, Santa

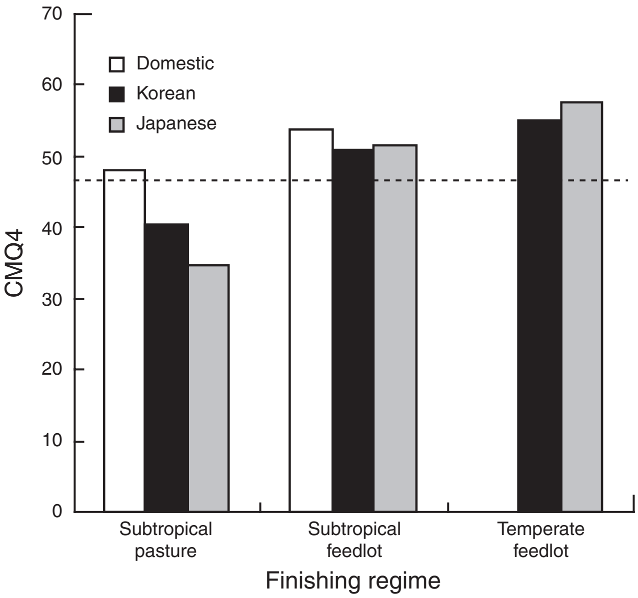

Fig. 3. Effect of finishing regime on Meat Standards Australia (MSA) clipped meat quality of four attributes score (CMQ4) at three market endpoints (n = 460). The line at CMQ4 46.5 indicates the minimum score for MSA 3-star grading.

Gertrudis and Belmont Red) reported in the Beef CRC Straightbreeding Program (Johnston *et al*. 2003). The main difference between CRC studies was the tropically adapted straightbreds had more desirable measurements for SFLT, ICLT and CLLT relative to the Brahman crossbreds in this experiment. In an unrelated study, Hearnshaw *et al*. (1999) reported higher cooking loss (P < 0.05) and lower sensory palatability (P < 0.05) of Brahmans relative to Angus sired steers from Hereford, Brahman and crossbred dams finished on pasture, consistent with our results for straightbred Brahmans relative to crossbreds.

An important outcome from this experiment is that carcasses with up to 75% *B. indicus* content can successfully meet minimum consumer palatability thresholds for objective and sensory measures of meat quality. Crossbreds with 50 and 75% *B. indicus* content did not differ significantly for objective and sensory meat quality traits, except for Continental crosses for SFST. Consistent findings were reported by Johnson *et al*. (1990) and Pringle *et al*. (1997) who found no significant difference in SF and sensory panel evaluation between Brahman × Angus steers with 50 and 75% Brahman content, feedlot finished in Florida in separate experiments. Wythes *et al*. (1989) reported no effect of genotype on SFLT, cooking loss or ultimate pH in 25–70% *B. indicus* content steers. On the other hand, Crouse *et al*. (1989) observed significant differences in SF and sensory panel scores for 50 *v*. 75% Brahman groups, concluding that as the percentage of Brahman content increased, sensory tenderness and juiciness decreased. In their study, processing practices were not controlled to the same extent as occurred in our study.

Muscle factors associated with breed differences in meat tenderness have been identified including the post-mortem rates of glycolysis and proteolysis, and connective tissue properties (Harper 1999; Ferguson *et al*. 2001; Ferguson 2002). Given IC measures for the LT and ST were lower than the 2.2 kg threshold considered tender by consumers (Gazzola 1997) and sire breeds did not differ (n.s.) for ICST, it would appear connective tissue toughness has limited market importance when Brahmans and Brahman crossbreds are slaughtered by 24 months of age. Other studies have also failed to find significant breed differences in collagen content and solubility (Johnson *et al*. 1990; Whipple *et al*. 1990). The myofibrillar component of muscle is believed to be the major contributor to tenderness variation (Johnson *et al*. 1990; Whipple *et al*. 1990; Shackelford *et al*. 1995; Harper 1999). Post-mortem rates of glycolysis and subsequent pH decline have been shown to be slower in *B. indicus* muscle relative to *B. taurus*, leading to increased shortening of the myofibrillar proteins (Wheeler *et al*. 1990; Shackelford *et al*. 1991). This may explain the higher (P < 0.001) SFLT of Brahmans relative to all other crosses except Shorthorn. However, we found no sire breed differences for ultimate pH in the LT or ST, which is consistent with other studies (Wythes *et al*. 1989; Whipple *et al*. 1990). As *B. indicus* content increases, an increase in calpastatin activity, and in some cases a decrease in calpain activity, leads to reduced myofibrillar degradation (Wheeler *et al*. 1990; Whipple *et al*. 1990; Shackelford *et al*. 1991, 1994; Pringle *et al*. 1997; Ferguson *et al*. 2000). This would support our finding that straightbred Brahmans had tougher SFLT and lower sensory palatability than crossbreds, but it does not explain our SFST results. However, studies by Whipple *et al*. (1990) and Shackelford *et al*. (1995) have shown that *B. indicus* inheritance increases SF of the LT to a greater extent than other muscles, and suggest SFLT is not a good predictor of SF of other muscles on the carcass.

Despite the poorer meat quality from straightbred Brahmans relative to Brahman crossbreds in this study, research has shown consumers can be satisfied with beef from 100% *B. indicus* cattle providing they are relatively young at slaughter and appropriate pre- and post-slaughter best practice (electrical stimulation, tenderstretch, aging) has been applied (Ferguson 2002). Genetic variation can be masked by variation due to environmental sources unless environment is closely controlled (Thompson 1999). Environmental sources of variation include growth path, immediate pre- and post-slaughter environments, the extent of proteolysis and the degree and duration of heat applied during cooking. Stress, physical activity pre-slaughter, animal age, use of HGP and intramuscular fat have all been implicated in meat toughness (Harper 1999). Relatively low genetic variation in comparison with environmental variation and inconsistent genetic correlations between tropical and temperate breeds suggest genetic improvement in tenderness may be less important than effective pre- and post-slaughter management protocols (Robinson *et al*. 2001). The management of an animal immediately pre-slaughter and the carcass processing conditions applied within the first 24 h post-slaughter have the largest influence on beef palatability, and can negate any genetic advantage in meat quality (Ferguson *et al*. 2001).

There was no one sire breed or breed type (British-, Continental- or tropically adapted-type) that excelled for meat quality across traits. Lack of evidence of breed interactions indicates cattle breeders can use a range of crossbred combinations and do not need to change sire breeds to target different markets, different finishing diets or different finishing environments within the constraints of this experiment.

Pasture v. *feedlot finishing*

Feedlot finishing of Brahman crossbreds is an important management component if tenderness is included in market specifications, regardless of market endpoint. Relative to pasture, feedlot finishing significantly improved all objective and sensory meat quality traits except CLST, and reduced age at slaughter by an average of 7 months (Schutt *et al*. 2009). Similarly, Bennett *et al*. (1995) reported that steers with no more than 50% Brahman content finished on rhizome peanut pasture in subtropical Florida had higher SF (6.8 *v.* 4.0 kg; $P < 0.001$), lower sensory juiciness ($P < 0.01$) and lower sensory tenderness ($P < 0.001$) relative to their feedlot-finished contemporaries. Ferguson *et al*. (2000) reported significant differences in SF ($P < 0.05$) and ultimate pH ($P < 0.001$) between pasture- and feedlot-finished carcasses in an experiment including Hereford, Brahman × Hereford and Brahman steers and heifers, with ~1 kg lower SF of feedlot-finished animals, and ultimate pH of 5.72 and 5.57 for pasture and feedlot finishing respectively. This is consistent with our results for SFLT and ultimate pH, though differences in PHLT and PHST between pasture and grain finishing in our experiment were much smaller. Johnston *et al*. (2003) reported consistent findings in magnitude and direction for SFLT, ICLT, SFST, ICST and CLLT in the Straightbreeding Program for Brahman, Belmont Red and Santa Gertrudis animals finished on pasture and grain in the subtropics. However, their CMQ4 results were lower for straightbred animals (40.9 *v.* 47.8 for pasture *v.* feedlot finishing respectively), relative to our results. In contrast, Allingham *et al*. (1998) reported no significant difference in SFST or ultimate pH between Brahman cross steers finished on three regimes including improved tropical pasture (uninterrupted growth) or low quality grass hay fed for 100 days followed by feedlot or pasture finishing for 157 days when slaughtered at hot carcass weights of 171–218 kg. Nonetheless, feedlot-finished animals had lower ($P < 0.05$) SF of pressure-heated ST samples, higher ($P < 0.05$) CLST and lower (n.s.) ICST than their pasture-finished contemporaries, which is consistent with our findings.

Negative effects on meat quality other than age at slaughter are apparent. At domestic market weights (25 months of age), objective measures of myofibrillar and connective tissue toughness of pasture-finished animals were outside acceptable tenderness limits. Furthermore, pasture-finished domestic animals had significantly higher ($P < 0.001$) SFLT and ICST than feedlot-finished Korean and Japanese market animals averaging 23 and 24 months of age respectively, suggesting a growth path effect on meat quality. Other studies and reviews have attributed differences in meat quality between pasture and feedlot finishing to age at slaughter, growth path (Allingham *et al*. 1998; Harper *et al*. 1999; Oddy *et al*. 2001; McKiernan and Wilkins 2009) and growth rate (Hearnshaw *et al*. 1995; Perry *et al*. 1999).

Subtropical v. *temperate finishing environments*

Finishing environment, including the possible inherent differences in pre- and post-slaughter processes between abattoirs and laboratories, had significant effects on objective and sensory meat quality. The higher ICST and OSSIF of temperate feedlot animals are inconsistent with their more desirable sensory palatability. Results for ICLT, ICST and SFST from the Straightbreeding Program (Johnston *et al*. 2003) were similar in magnitude but the reverse trend of these findings. Tropically adapted straightbreds (Brahman, Belmont Red, Santa Gertrudis) tended to have lower (more favourable) SFLT than our results. Similar to our findings though, Johnston *et al*. (2003) reported higher CMQ4 results for animals finished in the temperate feedlot. However, there was only a difference of 1.2 units for the tropically adapted straightbreds, whereas crossbreds in our experiment differed by 5.0 units. A study by Johnson *et al*. (1990) reported higher sensory panel ratings for loin steaks from calves finished in the cool season relative to their contemporaries finished in the warm season. This effect was attributed to a higher percentage of heat-soluble collagen in animals finished in the cool season resulting in more connective tissue break down during cooking. Our findings of no difference in SF between feedlots and higher sensory palatability of temperate feedlot-finished animals were consistent with those of Johnson *et al*. (1990).

Nutritional differences in seasonal pasture quality and quantity and interrupted growth of animals during the postweaning grow-out phase before feedlot entry (subtropical pasture *v.* temperate pasture) may have influenced meat quality characteristics between finishing environments. Growth path has an important influence on meat quality (Allingham *et al*. 1998; Harper 1999; Oddy *et al*. 2001; McKiernan and Wilkins 2009). Harper *et al*. (1997) reported that a period of severe nutritional restriction in an animal's growth path can influence the connective tissue toughness of its meat for at least 150 days following restriction, possibly as a result of increased intramuscular collagen turnover (Allingham *et al*. 1998). Findings from Allingham *et al*. (1998) are consistent with our results and may explain why subtropical feedlot animals, exposed to greater seasonal fluctuations of pasture quality and quantity during grow-out, had lower ICST ($P < 0.001$) than their temperate feedlot contemporaries. Nevertheless, we did not examine growth rates in this experiment and therefore cannot confidently say differences in growth path were causative of this effect.

Market effects

As animals age, increased collagen concentration is believed to be the primary contributor to increased meat toughness (Berge *et al*. 1997). Results indicate that connective tissue toughness and SFST increased as animals aged. Yet, except for SF in Japanese market animals, SFLT, SFST, ICLT and ICST were within acceptable tenderness levels, which may explain why consumer taste panels did not find a significant difference in sensory palatability between markets. In fact, there was only a difference of 2.4 units in CMQ4 between markets, lending further weight to the conclusion that connective tissue toughness was not a major issue for the meat of these animals.

This finding is supported by Johnston *et al*. (2003), who concluded that age-related changes in connective tissue toughness were not large in the Straightbreeding Program in animals up to 42 months of age. In contrast, market × finish interactions showed 12 months difference in age at slaughter for Japanese animals (36 *v.* 24 months of age) finished on pasture and feedlot, respectively, did result in significant detrimental effects on SFLT, SFST, ICLT and ICST ($P < 0.05$) and sensory palatability ($P < 0.05$) in this study. Therefore, myofibrillar and connective tissue toughness of Brahman crossbred animals has limited market importance up to 24 months of age unless they are finished on pasture.

Sex effects

Despite no difference in SFLT, ICLT and SFST between the sexes, heifers had significantly lower sensory meat quality scores than steers at domestic weights, which was consistent with results from the Straightbreeding Program (Johnston *et al*. 2003). In contrast to our findings, Johnston *et al*. (2003) reported heifers had higher SF and IC measures relative to steers. A study by Lawrence *et al*. (2001) found heifers advanced in skeletal and overall maturity at a much faster rate than steers, despite a lack of difference in SF, sensory tenderness or cooking loss between the sexes, supporting our OSSIF results. The significant sex effect on meat quality suggests heifers need to be finished differently to steers to attain similar eating quality. For example, palatability of heifers may be improved by increased time in feedlots. The lack of difference in SF, IC and sensory quality between the sexes when finished to Korean market weights supports the improved meat quality of heifers when grain fed for 100 days relative to domestic heifers fed for 70 days in this experiment.

Implications for industry breeding programs

Animals with up to 75% Brahman content can successfully meet minimum objective and sensory meat quality standards for tenderness. There was little evidence of important breed × finish and breed × market interactions on meat quality. Therefore, existing cattle breeding programs are suitable for pasture- and feedlot-finishing systems regardless of market endpoint, finishing regime or finishing environment. Connective tissue toughness was not important in Brahman crossbred animals before 24 months of age. Significant market × finish interactions for all meat quality traits show pasture finishing in subtropical environments is not desirable for Korean and Japanese market animals if meat tenderness is an important market consideration. Negative meat quality outcomes from subtropical pasture finishing appear to be due to a combination of seasonal nutritional availability and animal growth path. This may be negated by use of improved pastures, forage crops or supplementation to reduce weight stasis or loss during dry seasons. Negative effects of growth path on meat quality during grow-out can be overcome by feedlot finishing for a minimum of 70 days in subtropical or temperate feedlots to achieve acceptable levels of objective and sensory meat quality, with the added benefit of reduced age at slaughter. Heifers tend to have poorer sensory palatability than steers at common market weights which may be overcome by grain feeding for a longer period or grain feeding from an earlier age. The negative effects of inadequate pre- and post-slaughter management on meat quality should not be ignored, particularly as carcasses from straightbred Brahman cattle can meet minimum consumer palatability standards if best practice pre- and post-slaughter protocols are implemented. The MSA system is now rewarding beef producers with premium prices for every cut in every carcass that meets minimum eating quality standards for the domestic market.

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