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Long-term consequences of birth weight and growth to weaning on carcass, yield and beef quality characteristics of Piedmontese- and Wagyu-sired cattle

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Abstract. Cattle sired by Piedmontese or Wagyu bulls were bred and grown within pasture-based nutritional systems followed by feedlot finishing. Effects of low (mean 28.6 kg, $n = 120$) and high (38.8 kg, $n = 120$) birth weight followed by slow (mean 554 g/day, $n = 119$) or rapid (875 g/day, $n = 121$) growth to weaning on carcass, yield and beef quality characteristics at about 30 months of age were examined. Low birth weight calves weighed 56 kg less at 30 months of age, had 32 kg lighter carcasses, and yielded 18 kg less retail beef compared with high birth weight calves. Composition of carcasses differed little due to birth weight when adjusted to an equivalent carcass weight (380 kg). Calves grown slowly to weaning were 40 kg lighter at 30 months of age compared with those grown rapidly to weaning. They had 25 kg smaller carcasses which yielded 12 kg less retail beef than their counterparts at 30 months of age, although at an equivalent carcass weight yielded 5 kg more retail beef and had 5 kg less fat trim. Neither low birth weight nor slow growth to weaning had adverse effects on beef quality measurements. No interactions between sire-genotype and birth weight, or growth to weaning, were evident for carcass, yield and beef quality traits. Although restricted growth during fetal life or from birth to weaning resulted in smaller animals that yield less meat at about 30 months of age, adverse effects on composition due to increased fatness, or on indices of beef quality, were not evident at this age or when data were adjusted to an equivalent carcass weight.

Additional keywords: calf, composition, growth, meat, newborn, weaning.

Introduction

The beef industry in Australia is subject to variable pasture availability and quality as a result of factors including extremes in climate, soil quality and pasture species. This results in numerous growth path possibilities during the life of cattle that may influence their growth potential and body and carcass composition at slaughter for specific markets. Consequences of growth path during backgrounding and finishing of cattle in the feedlot or at pasture are relatively well understood. However, there is less information on the long-term consequences of growth during early-life of cattle managed within production systems that combine pasture-based nutrition during the post-weaning or backgrounding period with feedlot finishing (Greenwood *et al*. 2005).

It has been shown that increased growth rate during backgrounding and finishing increases intramuscular fat, carcass fatness (Robinson *et al*. 2001) and improves palatability (Perry and Thompson 2005). However, studies of cattle within pasture-based nutritional systems have failed to demonstrate substantial long-term differences in body or carcass composition due to prenatal nutrition and growth (Tudor *et al*. 1980) or on body or carcass composition and beef quality due to nutrition and growth from birth to weaning (Berge 1991; Hearnshaw 1997; Tudor *et al*. 1980). In contrast, severe nutritional restriction from birth to weaning followed by concentrate (high energy) feeding from weaning to slaughter resulted in increased fatness at the same live and carcass weights compared with

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cattle well-nourished to weaning (Tudor *et al*. 1980). Furthermore, the extent to which growth early in life interacts with genotype to influence long-term outcomes for carcass, yield and beef quality characteristics of cattle has not been investigated.

The objective of this study, therefore, was to investigate the hypotheses that prenatal growth experience (and by implication, prenatal nutrition) and pre-weaning growth have long-term consequences for carcass, yield and beef quality characteristics of cattle. We further hypothesised that sire-genotype may interact with nutrition early in life to influence carcass, yield and beef quality characteristics of cattle. To test these hypotheses, we investigated Piedmontese- and Wagyu-sired low and high birth weight cattle grown slowly or rapidly to weaning obtained from the study by Cafe *et al*. (2006) on factors influencing birth weight and growth to weaning. These cattle were backgrounded on pasture before feedlot finishing and slaughter at about 30 months of age, and descriptive statistics for their growth to slaughter are provided as background information to the findings on carcass, yield and beef quality characteristics.

Materials and methods

Animals, experimental design, management and growth early in life

Use of animals and the procedures performed in this study was approved by the North Coast Animal Care and Ethics Committee (Approval No. G2000/05).

The animals investigated were subsets of calves selected from a larger study of influences on birth weight and growth to weaning (Cafe *et al*. 2006) conducted at NSW Department of Primary Industries Grafton Agricultural Research and Advisory Station (GARAS: 29°39′S, 152°55′E, altitude 20 m). The experimental design was a 2 (low and high birth weight groups) × 2 (low and high pre-weaning growth groups) × 2 (Piedmontese and Wagyu sire-genotypes) × 3 (2001-born heifer and 2001- and 2002-born steer cohorts) factorial, with 9–11 calves in each of the 24 cells within the design. The cattle investigated were female (n = 80) or castrate (n = 160) progeny of 9 Piedmontese (n = 120 calves) or 8 Wagyu (n = 120 calves) bulls mated with Hereford cows. The 3 cohorts were: female calves born in 2001 (n = 81); castrate male calves born in 2001 (n = 79); and castrate male calves born in 2002 (n = 80). A total of 159 of the 303 castrate (52.8%) and 81 of 121 female (66.1%) calves available from the study by Cafe *et al*. (2006) were selected for the experiment.

The objectives for selection of calves into their respective birth weight (low, n = 120; high, n = 120) × pre-weaning growth (low, n = 119; high, n = 121) groups within each sire-genotype and cohort were established before the conduct of the study to represent extremes of prenatal and pre-weaning growth within the NSW North Coast region. These objectives were to achieve as close as possible to a 30% difference in birth weight coupled with an about 2-fold difference (0.5 *v.* 1.0 kg/day) in pre-weaning growth rate, ensuring the groups were as balanced as possible for sire, with about 10 calves per cell to facilitate meaningful comparisons of objective measurements of carcass, yield and beef quality characteristics. These criteria resulted in the low and high birth weight and low and high pre-weaning growth rate calves being selected from multi-modal distributions achieved by imposition of low or high maternal nutrition during pregnancy and lactation (see Cafe *et al*. 2006). The selection criteria for the low-low (LL), low-high (LH), high-low (HL) and high-high (HH) treatments resulted in 151 calves sourced from the matching LL, LH, HL and HH maternal nutritional treatments during lactation and pregnancy, whereas 89 calves sourced as a result of their phenotypic variation were allocated from non-matching maternal prenatal and/or lactational nutrition groups. To assess whether the method of sourcing the birth weight × pre-weaning growth groups was biased by inclusion of animals from matching and non-matching maternal nutrition groups, statistical analyses were performed for the entire dataset and for the sub-set of data comprising only those cattle obtained from the matching maternal nutrition groups. The significance of effects and predicted means differed little between the 2 datasets, hence, the results for the entire dataset are presented.

Birth weights, pre-weaning growth, and age and weight at weaning of the animals within the various birth weight × pre-weaning growth groups are presented in Table 1. Overall, the birth weight of calves was 10.2 kg (36%) greater in the high than in the low birth weight groups, and average daily gain to weaning was 301 g/day (58%) more rapid in the high than the low pre-weaning growth groups (Table 2). Weaning weight was 24 kg (14%) greater among the high birth weight calves than among the low birth weight calves, and 70 kg (46%) greater among the high pre-weaning growth calves than among their low growth counterparts.

Backgrounding nutrition, management and growth

Growth characteristics of the cattle during backgrounding are presented in Table 2. Following weaning at about 7 months of age, the calves were transported 150 km from Grafton to the NSW Department of Primary Industries Centre for Perennial Grazing Systems at Glen Innes (l29°44′S, 151°42′E, altitude 1057 m) where they were backgrounded on improved temperate perennial pastures until feedlot entry at about 26 months of age.

Each cohort grazed as a single group during backgrounding. When necessary, the cattle were provided with cottonseed as a meal or pellets (9.4 MJ ME, 380 g crude protein (CP) and 286 g ADF per kg DM), a pelleted supplementary feed (11.5 MJ ME, 130 g CP and 240 g acid detergent fibre (ADF) per kg DM: Performance Pellets, Oleo Industries, Moree, NSW) and roughage (hay or silage) to ensure growth was not retarded below 0.5 kg gain/day for prolonged periods. The 2001 heifer and steer cohorts required supplementation with cottonseed from July to September 2002 and pellets (up to 3 kg/head.day) and roughage from September 2002 until February 2003 as drought resulted in little available pasture. The heifer cohort required further supplementation with pellets (up to 4 kg/head.day) from July 2003 until feedlot entry to ensure target weights (average about 450 kg liveweight for heifers and 500 kg liveweight for steers) were met. The 2002 steer cohort was supplemented with pellets (2 kg/head.day) only during September 2004 as pasture conditions were adequate for the remainder of the post-weaning period.

Feedlot entry weight was 39 kg (7.5%) lower among low birth weight calves compared with the heavier newborns, and high pre-weaning growth calves were 34 kg (7.0%) heavier at feedlot entry than the low pre-weaning growth calves (Table 2).

Feedlot management, nutrition and growth

Growth characteristics of the cattle during feedlotting are presented in Table 2. Following backgrounding, the cattle were transported 160 km from Glen Innes to the Cooperative Research Centre for Cattle and Beef Quality's 'Tullimba' feedlot located at Kingston, NSW (30°30′S, 151°10′E, altitude 560 m). At induction they were weighed, tagged with electronic identification eartags, vaccinated against clostridial diseases, and treated for internal and external parasites. The 2001-born steer cohort was run as 1 group during feedlotting for 109 days. The 2001-born heifer and the 2002-born steer cohorts were allocated to pens, each containing an automatic, group feeding and weighing facility that allowed intake and weight of each individual to be measured, using an iterative process that balanced each pen of 10 cattle for treatment groups and liveweight. The 2001-born heifer cohort remained in the feedlot for 123 days and the 2002-born steer cohort for 120 days. The cattle were fed a grain-based diet. The diet for the 2001-born cohorts contained 12.1 MJ ME, 133 g crude protein and 101 g fibre (ADF) per kg dry matter (DM), and that for the 2002-born cohort 12.0 MJ ME, 157 g crude protein and 125 g ADF per kg DM as determined at the laboratory of CASCO Agritech, Toowoomba, Qld. Adaptation to the feedlot diet occurred over a 3-week period. The cattle exited the feedlot to be slaughtered as a single group within each cohort at about 30 months of age.

Feedlot exit weight was 56 kg (8.7%) greater among high compared with low birth weight cattle. High pre-weaning growth group cattle were 40 kg (6.1%) heavier at feedlot exit than their low growth counterparts (Table 2).

Slaughter procedures and measurements

Cattle were transported 370 km (6 h) from ‘Tullimba’ to John Dee Pty Ltd abattoir, Warwick, Qld, on the day before slaughter and penned overnight until slaughter the next day. Each animal was slaughtered by captive bolt stunning and exsanguination and standard carcasses prepared (AUS-MEAT 1998) and split into 2 sides. Carcasses were treated with low voltage (400 mA) electrical stimulation for 20 s immediately after death. Rump (P8) fat depth was measured on each carcass, and both sides were weighed before entering the chiller.

Carcass chiller assessments and yield measurements

Carcass sides were chilled overnight, and when the temperature of the loin was below 11°C they were quartered between the 12th and 13th ribs. No less than 20 min after quartering, sides were MSA graded (MSA 1999), whereby eye muscle area, rib fat depth, ossification score and marble score (AUS-MEAT 1998) were determined for each carcass. One side of each carcass was commercially boned-out at the abattoir to determine the weight of retail beef yield, fat trim and bone. Cuts were trimmed to a 5 mm fat depth over all cuts. Recovery of boned-out components was 99.0 ± 1.0% (mean ± s.d.) of cold side weights.

Objective beef quality and intramuscular fat measurements

The *mm. longissimus lumborum* (striploin) and *semitendinosus* (eye round) were removed during commercial bone-out, vacuum packaged and frozen at –20°C. Sample preparation and measurement of ultimate pH, colour [lightness (L*), red/green (a*), yellow/blue (b*)], colour space, texture (shear force and compression), cooking loss, and intramuscular fat percentage (determined by near infrared spectrophotometry) were performed as described by Perry *et al.* (2001). Each of these measurements was made on the *m. longissimus lumborum*, whilst only shear force, compression and cooking loss were determined for the *m. semitendinosus*.

Table 1. Mean characteristics at birth and to weaning of calves (*n* = 240) used to study consequences of growth early in life

n, number of cattle. Within each sire-breed and sex cohort, groups are ranked according to weaning weight from lowest to highest. Values are unadjusted mean ± s.d.

Birth weight group	Pre-weaning growth group	*n*	Birth weight (kg)	Pre-weaning ADG (g/day)	Pre-weaning gain (kg)	Weaning weight (kg)	Weaning age (days)
			2001-born Wagyu-sired heifers				
Low	Low	10	25.9 ± 2.9	462 ± 121	103 ± 27	129 ± 28	222 ± 17
High	Low	11	33.5 ± 2.5	598 ± 118	127 ± 36	161 ± 36	209 ± 22
Low	High	10	25.9 ± 2.5	744 ± 97	162 ± 28	188 ± 28	217 ± 25
High	High	10	34.5 ± 2.7	838 ± 58	171 ± 19	205 ± 18	203 ± 14
			2001-born Piedmontese-sired heifers				
Low	Low	10	28.2 ± 3.2	406 ± 115	88 ± 30	116 ± 29	215 ± 21
High	Low	9	37.4 ± 4.0	531 ± 125	107 ± 25	145 ± 27	203 ± 18
Low	High	10	29.3 ± 3.4	763 ± 89	165 ± 25	194 ± 26	216 ± 18
High	High	11	38.3 ± 3.2	871 ± 111	187 ± 27	225 ± 26	215 ± 21
			2001-born Wagyu-sired steers				
Low	Low	10	26.5 ± 3.7	515 ± 62	112 ± 13	138 ± 14	218 ± 18
High	Low	9	35.8 ± 1.9	572 ± 119	126 ± 30	161 ± 30	219 ± 22
Low	High	10	28.4 ± 2.5	872 ± 76	196 ± 27	224 ± 28	224 ± 20
High	High	10	37.6 ± 3.3	958 ± 79	203 ± 27	241 ± 27	212 ± 22
			2001-born Piedmontese-sired steers				
Low	Low	10	30.7 ± 2.3	552 ± 63	122 ± 19	153 ± 18	221 ± 22
High	Low	10	41.1 ± 3.5	591 ± 131	119 ± 25	160 ± 27	203 ± 23
Low	High	10	32.1 ± 4.3	856 ± 125	188 ± 27	220 ± 29	220 ± 21
High	High	10	43.0 ± 4.6	942 ± 135	203 ± 39	246 ± 40	214 ± 15
			2002-born Wagyu-sired steers				
Low	Low	10	27.2 ± 2.8	589 ± 45	127 ± 19	154 ± 19	214 ± 23
High	Low	10	38.7 ± 2.7	660 ± 73	138 ± 11	176 ± 10	210 ± 25
Low	High	10	26.4 ± 2.6	880 ± 84	188 ± 26	214 ± 27	214 ± 20
High	High	10	40.6 ± 2.2	943 ± 74	199 ± 19	240 ± 19	212 ± 19
			2002-born Piedmontese-sired steers				
Low	Low	10	31.1 ± 5.4	556 ± 87	116 ± 18	147 ± 20	209 ± 22
High	Low	10	42.3 ± 2.7	615 ± 71	126 ± 14	169 ± 15	206 ± 19
Low	High	10	31.2 ± 4.3	843 ± 61	185 ± 27	216 ± 25	219 ± 22
High	High	10	42.9 ± 3.6	992 ± 83	200 ± 25	243 ± 27	201 ± 16

Table 2. Mean (± s.d.) growth and liveweight characteristics of cattle (*n* = 240) varying in birth weight, pre-weaning growth, sire genotype, and cohort

n, number of cattle
Post-weaning gain and ADG is from weaning to feedlot exit

	n	Birth weight (kg)	Pre-weaning ADG (g/day)	Weaning weight (kg)	Background ADG (g/day)	Background gain (kg)	Feedlot entry weight (kg)	Feedlot ADG (g/day)	Feedlot gain (kg)	Feedlot exit weight (kg)	Post-weaning ADG (g/day)	Post-weaning gain (kg)
						Birth weight						
Low	120	28.6 ± 4.3	670 ± 188	174 ± 44	571 ± 75	317 ± 42	481 ± 49	1481 ± 302	167 ± 41	648 ± 70	696 ± 86	473 ± 59
High	120	38.8 ± 3.9	762 ± 196	198 ± 45	602 ± 70	334 ± 39	520 ± 47	1620 ± 366	183 ± 50	703 ± 78	742 ± 96	505 ± 68
						Pre-weaning growth						
Low	119	33.1 ± 6.4	554 ± 115	151 ± 28	615 ± 70	341 ± 39	483 ± 47	1531 ± 325	173 ± 45	656 ± 75	742 ± 92	505 ± 65
High	121	34.2 ± 6.8	875 ± 114	221 ± 32	558 ± 68	310 ± 37	517 ± 50	1570 ± 358	177 ± 49	695 ± 78	696 ± 90	473 ± 63
						Sire						
Wagyu	120	31.7 ± 6.0	713 ± 207	186 ± 44	579 ± 75	321 ± 42	496 ± 53	1520 ± 318	172 ± 44	667 ± 78	708 ± 93	482 ± 65
Piedmontese	120	35.7 ± 6.6	719 ± 187	187 ± 49	593 ± 73	329 ± 40	505 ± 50	1582 ± 363	179 ± 49	684 ± 79	730 ± 94	496 ± 66
						Cohort						
2001-born heifers	81	31.7 ± 5.5	655 ± 195	171 ± 45	542 ± 73	302 ± 41	468 ± 47	1398 ± 217	158 ± 25	626 ± 60	666 ± 75	454 ± 51
2001-born steers	79	34.4 ± 6.5	734 ± 205	193 ± 49	610 ± 55	339 ± 30	520 ± 46	1358 ± 183	140 ± 19	659 ± 54	695 ± 59	466 ± 40
2002-born steers	80	35.0 ± 7.2	760 ± 177	195 ± 41	607 ± 73	336 ± 40	514 ± 45	1893 ± 303	227 ± 36	741 ± 72	796 ± 90	546 ± 62

Statistical analyses

Associations between the set of measured variables and the animal classification factors generated by the experimental design were examined by fitting linear models using restricted maximum likelihood (REML). Factors in each model included terms for birth weight category, pre-weaning growth category, sire genotype, sex of calf and year-born. The absence of 2002-born heifers in this study meant that effects due to breeding cycle or year of birth were not separable from those due to calf sex and so a 3 level 'cohort' indicator (2001-born heifer; 2001-born steer; 2002-born steer) was used as a proxy term for the combined effects of calf sex and breeding cycle. Terms to allow for first order interactions between the main factors were also included in each model. An additional animal based covariate (HSCW) was included in the models when appropriate. The statistical importance of each term was assessed by construction of analysis of variance tables.

The models enabled prediction of the response for any factor or combination of factors averaged over the remaining factors, and these predictions were used to summarise and discuss the data.

Modelling was performed through use of the GENSTAT software (Payne and Arnold 1997), with statistical significance of main effects, interactions and covariates accepted at $P<0.05$.

Results

Data for carcass, yield and beef quality characteristics were examined to establish effects using least squares means from actual values and using predicted values using HSCW as a covariate to enable comparisons at equivalent carcass weight (380 kg).

Carcass characteristics

Hot standard carcass weight

Hot standard carcasses were 30 kg (7.6%) lighter in low compared with high birth weight cattle, and low pre-weaning growth cattle had carcasses that weighed 25 kg (6.4%) less than those of the high growth group at about 30 months of age (Table 3). Carcasses of Piedmontese-sired cattle were 8 kg (4.1%) heavier than those of Wagyu-sired cattle. Overall, steers born in 2001 had carcasses 21 kg (6.0%) heavier than heifers born in the same year, and 42 kg (10%) lighter than the steers born in 2002. However, an interaction between birth weight and cohort was evident due to the steers born in 2001 having heavier carcasses than heifers born in 2001 (s.e.d. = 5.8 kg) within the low birth weight group (365 *v.* 335 kg) but not within the high birth weight group (381 *v.* 370 kg, respectively).

Dressing percentage

Dressing percentage did not differ due to birth weight, and was 0.4% of liveweight greater among the high than the low pre-weaning growth group at about 30 months of age (Table 3). Piedmontese-sired cattle dressed 1.5% of liveweight heavier than the Wagyu-sired cattle, and the 2001-born steers dressed 0.6% of liveweight heavier than the steers born in 2002.

Dressing percentage was 0.4% of liveweight greater among low than high birth weight cattle at an equivalent

Table 3. Predicted means for characteristics of beef carcasses ($n = 240$) at about 30 months of age and when adjusted to equivalent carcass weight (380 kg), as affected by birth weight, pre-weaning growth, sire genotype, and cohort

n, number of cattle. Values are least squares means and adjusted values are least squares means using HSCW (W_l linear or W_q quadratic if significant) as a covariate, and appropriate s.e.d. for each comparison. Significant ($P<0.05$) main effects and interactions are shown for each variable

	n	HSCW (kg)	Dressing percentage	Adjusted dressing percentage	Eye muscle area (cm^2)	Adjusted eye muscle area (cm^2)	Ossification score (100–590)	Adjusted ossification score (100–590)
				Birth weight (B)				
Low	120	364	56.3	56.5	88.2	90.4	203	206
High	120	396	56.4	56.1	91.1	88.9	198	195
s.e.d.	—	3.9	0.17	0.18	1.18	1.17	3.6	4.0
				Pre-weaning growth (P)				
Low	119	368	56.1	56.3	88.3	90.1	199	202
High	121	393	56.5	56.3	91.0	89.2	201	199
s.e.d.	—	3.9	0.17	0.17	1.18	1.15	3.6	3.9
				Sire-genotype (G)				
Wagyu	120	371	55.6	55.7	85.4	86.8	196	198
Piedmontese	120	390	57.1	56.9	93.9	92.5	204	203
s.e.d.	—	3.9	0.17	0.17	1.18	1.11	3.6	3.7
				Cohort (C)				
2001-born heifers	81	352	56.4	56.8	87.9	91.7	256	261
2001-born steers	79	373	56.6	56.6	85.1	86.5	177	178
2002-born steers	80	415	56.0	55.5	95.9	90.8	168	161
s.e.d.	—	4.8	0.21	0.26	1.45	1.74	4.4	5.8
Main effects	—	B,P,G,C	P,G,C	B,G,C,W_q	B,P,G,C	G,C,W_q	G,C	B,C,W_l
Interactions	—	B × C	—	—	B × C	B × P, G × C	G × C	G × C

carcass weight, and did not differ due to pre-weaning growth (Table 3). Piedmontese-sired cattle dressed 1.2% of liveweight heavier than the Wagyu-sired cattle. The 2001-born heifers dressed 1.3% of liveweight heavier and the 2001-born steers 1.1% of liveweight heavier than the steers born in 2002.

Eye muscle area

Eye muscle area was 2.9 cm^2 (3.3%) greater among the high compared with the low birth weight cattle at about 30 months of age (Table 3). High pre-weaning growth cattle had an eye muscle area 2.7 cm^2 (3.1%) greater than the low pre-weaning growth cattle. Eye muscle area was 8.5 cm^2 (10%) greater among Piedmontese-sired than among Wagyu-sired cattle. Steers born in 2002 had an eye muscle area 10.8 cm^2 (13%) greater than those born in 2001, and 8.0 cm^2 (9.1%) greater than heifers born in 2001. A birth weight × cohort interaction was evident for eye muscle area (s.e.d. = 2.06 cm^2). High birth weight cattle had greater eye muscle area than low birth weight cattle within the 2001-born heifers (90.4 *v.* 85.3 cm^2) and 2002-born steers (98.4 *v.* 93.4 cm^2) but not within the 2001-born steers (84.4 *v.* 85.9 cm^2, respectively).

An interaction between birth weight and pre-weaning growth was evident for eye muscle area at an equivalent carcass weight (s.e.d. = 1.82 cm^2). Low birth weight calves had greater eye muscle area than high birth weight calves within the high pre-weaning growth group (91.1 *v.* 87.2 cm^2), whereas eye muscle area did not differ between low and high birth weight cattle within the low pre-weaning growth group (89.8 *v.* 90.5 cm^2, respectively). Eye muscle area was 5.7 cm^2 (6.6%) larger among Piedmontese-sired than among Wagyu-sired cattle at 380 kg carcass weight (Table 3). Steers born in 2001 had an eye muscle area 5.2 cm^2 (5.7%) smaller than heifers born in 2001, and 4.3 cm^2 (4.7%) smaller than steers born in 2002. A sire-genotype × cohort interaction was also evident for eye muscle area (s.e.d. = 2.35 cm^2) at the same carcass weight. Piedmontese-sired cattle had greater eye muscle area than Wagyu-sired cattle within the 2001-born heifers (96.3 *v.* 87.0 cm^2) and 2002-born steers (93.7 *v.* 87.9 cm^2) but not within the 2001-born steers (87.6 *v.* 85.4 cm^2, respectively).

Ossification score

Ossification score at about 30 months of age did not differ due to birth weight or pre-weaning growth (Table 3). Piedmontese-sired cattle had an 8 unit (4.1%) greater ossification score than Wagyu-sired cattle. Heifers born in 2001 had a 79 unit (45%) greater ossification score than steers born in the same year, and an 88 unit (52%) greater score than steers born the following year. Steers born in 2001 had a 9 unit (5.3%) greater ossification score than steers born

Table 4. Predicted means for beef carcass (*n* = 240) fatness characteristics at about 30 months of age and when adjusted to equivalent carcass weight (380 kg), as affected by birth weight, pre-weaning growth, sire genotype, and cohort

n, number of cattle. Values are least squares means and adjusted values are least squares means using HSCW (W_l linear or W_q quadratic if significant) as a covariate, and appropriate s.e.d. for each comparison. Significant (P<0.05) main effects and interactions are shown for each variable

	n	P8 fat depth (mm)	Adjusted P8 fat depth (mm)	Rib fat depth (mm)	Adjusted rib fat depth (mm)	Marble score (0–6)	Adjusted marble score (0–6)	*M. longissimus* intramuscular fat (%)	Adjusted *m. longissimus* intramuscular fat (%)
Birth weight (B)									
Low	120	20.4	21.3	11.2	11.5	1.84	1.83	6.98	6.91
High	120	20.5	19.6	12.1	11.8	1.86	1.86	6.88	6.95
s.e.d.	—	0.85	0.94	0.40	0.45	0.100	0.114	0.294	0.334
Pre-weaning growth (P)									
Low	119	19.3	20.1	11.0	11.3	1.93	1.92	6.93	6.88
High	121	21.6	20.8	12.3	12.0	1.76	1.77	6.93	6.98
s.e.d.	—	0.85	0.90	0.40	0.43	0.100	0.109	0.294	0.321
Sire-genotype (G)									
Wagyu	120	23.3	23.9	13.2	13.4	2.38	2.37	8.82	8.77
Piedmontese	120	17.6	17.0	10.1	9.9	1.32	1.32	5.05	5.09
s.e.d.	—	0.85	0.86	0.40	0.41	0.100	0.105	0.294	0.309
Cohort (C)									
2001-born heifers	81	24.7	26.4	12.6	13.2	1.57	1.56	7.16	7.04
2001-born steers	79	18.3	18.7	11.8	11.9	1.97	1.96	6.95	6.92
2002-born steers	80	18.4	16.3	10.5	9.8	2.00	2.01	6.68	6.83
s.e.d.	—	1.05	1.34	0.49	0.63	0.122	0.163	0.361	0.477
Main effects	—	P, G, C	B, G, C	B, P, G, C	G, C	G, C	G, C	G	G, W_l
Interactions	—	—	—	G × C	—	—	—	—	—

in 2002. There was an interaction between sire-genotype and cohort for ossification score at 30 months of age (s.e.d. = 6.3 units). Piedmontese-sired cattle had a higher score than Wagyu-sired cattle within the 2001-born heifer group (270 *v.* 243 units) but not within the steers born in 2001 (176 *v.* 177 units, respectively) and 2002 (167 *v.* 168 units).

Ossification score at 380 kg carcass weight was 11 units (5.6%) greater in low compared with high birth weight cattle, and did not differ overall due to pre-weaning growth (Table 3). At the same carcass weight, heifers born in 2001 had an 83 unit (47%) greater ossification score than steers born in the same year, and a 100 unit (62%) greater score than steers born the following year. Steers born in 2001 had a 16 unit (10%) greater ossification score than steers born in 2002. There was a sire-genotype × cohort interaction for ossification score at equivalent carcass weight (s.e.d. = 7.8 units). Piedmontese-sired cattle had a higher score than Wagyu-sired cattle within the 2001-born heifer group (274 *v.* 249 units) but not within the steers born in 2001 (175 *v.* 181 units, respectively) or 2002 (158 *v.* 164 units).

P8 fat depth

Fat depth at the P8 (rump) site did not differ between birth weight groups at about 30 months of age, but was 2.3 mm (12%) greater among high compared with low pre-weaning growth group cattle (Table 4). Wagyu-sired cattle had 5.7 mm (32%) greater P8 fat depth than those of Piedmontese sires. Heifers born in 2001 had 6.4 mm (35%) greater P8 fat depth than steers born in the same year and 6.3 mm (34%) more than steers born the following year.

Fat depth at the P8 site was 1.7 mm (8.7%) greater among low than high birth weight cattle at the same carcass weight, but did not differ between low and high pre-weaning growth groups (Table 4). Wagyu-sired cattle had 6.9 mm (41%) greater P8 fat depth than those of Piedmontese sires. Heifers born in 2001 had 7.7 mm (41%) greater P8 fat depth than steers born in 2001 and 10.1 mm (62%) greater P8 fat depth than the steers born in 2002.

Rib fat depth

Rib fat depth was 0.9 mm (7.4%) less in low than in high birth weight calves and was 1.3 mm (12%) greater in high than in low pre-weaning growth group cattle at about 30 months of age (Table 4). Wagyu-sired cattle had 3.1 mm (31%) greater rib fat depth than Piedmontese-sired cattle. Steers born in 2002 had 1.3 mm (11%) less rib fat depth at 30 months of age than steers born in 2001 and 2.1 mm (17%) less than heifers born in 2001. An interaction between genotype and cohort for rib fat depth was evident (s.e.d. = 0.70 mm). Among Wagyu-sired cattle, steers born in 2002 (11.4 mm) had less rib fat depth than 2001-born heifers (14.7 mm) and 2001-born steers (13.4 mm). Differences in

Table 5. Predicted means for yield characteristics of beef carcasses ($n = 240$) at about 30 months of age and when adjusted to equivalent carcass weight (380 kg), as affected by birth weight, pre-weaning growth, sire genotype, and cohort

n, number of cattle. Values are least squares means and adjusted values are least squares means using HSCW (W_l linear or W_q quadratic if significant) as a covariate, and appropriate s.e.d. for each comparison. Significant ($P<0.05$) main effects and interactions are shown for each variable

	n	Retail yield (kg)	Adjusted retail yield (kg)	Bone (kg)	Adjusted bone (kg)	Fat trim (kg)	Adjusted fat trim (kg)
			Birth weight (B)				
Low	120	239	249	64.3	66.9	52.3	54.6
High	120	257	247	70.2	67.9	58.3	56.0
s.e.d.	—	2.7	1.1	0.81	0.55	1.17	1.17
			Pre-weaning growth (P)				
Low	119	242	251	65.7	67.8	50.9	52.8
High	121	254	246	68.8	66.7	59.6	57.8
s.e.d.	—	2.7	1.1	0.81	0.55	1.17	1.12
			Sire-genotype (G)				
Wagyu	120	233	240	66.2	67.8	62.0	63.3
Piedmontese	120	263	257	68.3	66.8	48.6	47.2
s.e.d.	—	2.7	1.0	0.81	0.53	1.17	1.08
			Cohort (C)				
2001-born heifers	81	230	248	58.7	63.3	54.3	58.4
2001-born steers	79	244	248	67.3	68.4	54.5	55.2
2002-born steers	80	270	248	75.8	70.1	57.1	52.2
s.e.d.	—	3.4	1.6	0.99	0.82	1.44	1.68
Main effects	—	B, P, G, C	P, G, W_l	B, P, G, C	C, W_l	B, P, G	P, G, C, W_q
Interactions	—	B × C	—	B × C	—	—	—

rib fat depth were not apparent between cohorts of Piedmontese-sired cattle.

Rib fat depth did not differ overall due to birth weight or pre-weaning growth group at 380 kg carcass weight (Table 4). At the same carcass weight, Wagyu-sired cattle had 3.5 mm (35%) greater rib fat depth than Piedmontese-sired cattle. Steers born in 2001 had 2.1 mm (21%) and heifers born in 2001 had 3.4 mm (35%) greater rib fat depth than steers born in 2002.

Marble score

Marble score did not differ at about 30 months of age due to birth weight or pre-weaning growth (Table 4). Wagyu-sired cattle had marble scores 1.06 units (80%) greater than their Piedmontese-sired counterparts. Steers born in 2001 and 2002 had marble scores 0.40 (25%) and 0.43 units (27%) greater, respectively, than the 2001-born heifers at 30 months of age.

Marble score did not differ at 380 kg carcass weight due to birth weight or pre-weaning growth (Table 4). Wagyu-sired cattle had marble scores 1.05 units (80%) higher than their Piedmontese-sired counterparts. Steers born in 2001 and 2002 had marble scores 0.40 units (26%) and 0.45 units (29%) greater, respectively, than the 2001-born heifers.

Intramuscular fat percentage

Intramuscular fat percentage in the *m. longissimus* (Table 4) was significantly greater in the Wagyu- than in the Piedmontese-sired cattle at about 30 months of age (8.82 *v.* 5.05%) and at an equivalent carcass weight (8.77 *v.* 5.09%). There were no significant effects of birth weight, pre-weaning growth or cohort on intramuscular fat percentage.

Yield characteristics

Retail beef yield

Retail beef yield was 18 kg (7.0% of weight of retail yield) less overall for low compared with high birth weight cattle at about 30 months of age (Table 5). However, there was a birth weight × cohort interaction (s.e.d = 4.8 kg) with high and low birth weight cattle differing in retail yield within the 2002-born steers (284 *v.* 257 kg, respectively) and 2001-born heifers (240 *v.* 220 kg) but not significantly so within the 2001-born steers (248 *v.* 240 kg). High pre-weaning growth cattle produced 12 kg (5.0%) more retail beef than their low growth counterparts at 30 months of age. Piedmontese-sired cattle produced 30 kg (13%) more retail beef than Wagyu-sired cattle. Overall, steers born in 2002 had retail beef yields 26 kg (11%) greater than steers born in 2001 and 40 kg (17%) greater yield than heifers born in 2001, and retail yield was 14 kg (6.1%) greater for the 2001-born steers than the 2001-born heifers at 30 months of age.

Retail yield at equivalent carcass weight did not differ due to birth weight. Low pre-weaning growth cattle produced 5 kg (2.0%) more retail beef at 380 kg carcass weight than the high pre-weaning growth cattle (Table 5). Piedmontese-sired cattle yielded 17 kg (7.1%) more retail beef than Wagyu-sired cattle, while there was no effect of cohort on retail beef yield at the same carcass weight.

Carcass bone

Weight of bone was 5.9 kg (8.4%) greater in high compared with low birth weight calves at about 30 months of age, and 3.1 kg (4.7%) greater for high than for low pre-weaning growth cattle (Table 5). Piedmontese-sired cattle had 2.1 kg (3.2%) more bone than Wagyu-sired cattle at the same age. Steers born in 2002 had 8.5 kg (12.6%) more bone than steers born in 2001, and 11.4 kg (19%) more bone than 2001-born heifer group who also had 8.6 kg (13%) less bone than 2001-born steers. Although high birth weight cattle had more bone than their low birth weight counterparts within all cohorts (s.e.d. = 1.41 kg), the magnitude of the difference between birth weight groups was greater among 2002-born steers (79.9 *v.* 71.7 kg) and 2001-born heifers (61.9 *v.* 55.6 kg) than among 2001-born steers (68.9 *v.* 65.7 kg).

Weight of bone did not differ significantly because of birth weight, pre-weaning growth or sire-genotype at 380 kg carcass weight (Table 5). Heifers born in 2001 had 5.1 kg (7.5%) less bone than 2001-born steers and 6.8 kg (9.7%) less bone at the same carcass weight than steers born in 2002, while the steers born in 2001 had 1.7 kg (1.4%) less bone than those born in 2002.

Carcass fat trim

Weight of fat trim was 6.0 kg (11.4%) greater in high compared with low birth weight cattle at about 30 months of age (Table 5). High pre-weaning growth cattle had 8.7 kg (17%) more fat trim at the same age as the low pre-weaning growth cattle. Cattle sired by Wagyu bulls had 13.4 kg (27.6%) more fat trim than those sired by Piedmontese bulls, while weight of fat trim did not differ due to cohort at 30 months of age.

Fat trim at 380 kg carcass weight carcass weight did not differ due to birth weight, but was 5.0 kg (9.5%) greater among high compared with low pre-weaning growth cattle (Table 5). At the same carcass weight, cattle sired by Wagyu bulls had 16.1 kg (34.1%) more fat trim than those sired by Piedmontese bulls, while Heifers born in 2001 had 6.2 kg (12%) more fat trim than steers born in 2002.

Beef quality

Significance of effects on beef quality were unchanged when assessed at about 30 months of age and at 380 kg carcass weight, hence results are only presented for the cattle at about 30 months of age (Table 6).

Shear force

Shear force in the *m. longissimus lumborum* and the *m. semitendinosus* was not significantly affected by birth weight or pre-weaning growth (Table 6). The 2001-born

Table 6. Predicted means for *m. longissimus lumborum* (striploin) and *m. semitendinosus* (eye round) beef quality characteristics (*n* = 240) at about 30 months of age as affected by birth weight, pre-weaning growth, sire genotype, and cohort

n, number of cattle. Values are least squares means and appropriate s.e.d. for each comparison. Significant (*P*<0.05) main effects and interactions are shown for each variable

	n	*M. longissimus lumborum*							*M. semitendinosus*		
		Shear force (kg)	Compression (kg)	Cooking loss (%)	Ultimate pH	Colour L*	Colour a*	Colour b*	Shear force (kg)	Compression (kg)	Cooking loss (%)
Birth weight (B)											
Low	120	3.98	1.42	21.6	5.48	39.4	26.3	13.5	4.71	2.33	21.5
High	120	4.15	1.47	21.6	5.48	40.1	26.7	13.8	4.73	2.27	21.3
s.e.d.	—	0.116	0.035	0.24	0.006	0.34	0.23	0.15	0.083	0.054	0.22
Pre-weaning growth (P)											
Low	119	4.13	1.45	21.9	5.48	39.8	26.4	13.7	4.73	2.31	21.5
High	121	4.00	1.44	21.4	5.47	39.7	26.6	13.7	4.71	2.30	21.3
s.e.d.	—	0.116	0.035	0.24	0.006	0.34	0.23	0.15	0.083	0.054	0.22
Sire-genotype (G)											
Wagyu	120	4.06	1.39	21.2	5.48	40.2	26.7	13.8	4.97	2.33	21.4
Piedmontese	120	4.07	1.50	21.9	5.47	39.3	26.4	13.6	4.47	2.28	21.3
s.e.d	—	0.116	0.035	0.24	0.006	0.34	0.23	0.15	0.083	0.054	0.22
Cohort (C)											
2001-born heifers	81	3.87	1.37	21.3	5.44	38.6	26.2	13.6	4.30	2.19	21.4
2001-born steers	79	4.57	1.65	24.6	5.47	39.8	26.2	13.5	5.37	2.70	24.4
2002-born steers	80	3.75	1.31	19.0	5.52	40.8	27.2	14.0	4.50	2.02	18.3
s.e.d.	—	0.143	0.042	0.29	0.008	0.42	0.29	0.19	0.101	0.067	0.27
Main effects	—	C	G, C	P, G, C	C	G, C	C	C	G, C	C	C
Interactions	—	—	—	—	—	—	—	—	—	—	—

steers had a greater shear force in both muscles than their respective counterparts. The Wagyu-sired cattle had greater shear force than the Piedmontese-sired cattle in the *semitendinosus* but not the *longissimus* muscle.

Compression

Effects of birth weight and pre-weaning growth on compression were not evident (Table 6). The Piedmontese-sired cattle had greater compression than the Wagyu-sired cattle in the *m. longissimus lumborum*. The 2001-born steers had a greater compression in both muscles than the other cohorts.

Cooking loss

The low pre-weaning growth cattle had greater cooking losses in the *m. longissimus lumborum* than their high growth counterparts, while birth weight had no effect on cooking loss. Piedmontese-sired cattle had more cooking losses in the *longissimus* muscle than those sired by Wagyu (Table 6). The steers born in 2001 had greater cooking loss in both muscles than the other cohorts, and the 2001-born heifers more cooking losses in both muscles than the 2002-born steers.

Ultimate pH

Ultimate pH in the *m. longissimus* was not affected by birth weight, pre-weaning growth or sire-genotype, but differed between each of the cohorts (Table 6).

Colour

Colour measurements of the *m. longissimus lumborum* were not affected by birth weight or pre-weaning growth group (Table 6). Wagyu-sired cattle had higher L* (lightness) values than the Piedmontese-sired cattle. The 2002-born steers had higher L* values than the 2001-born steers, which had higher values than the 2001-born heifers. The a* (red/green) and b* (yellow/blue) values were higher for the 2002-born steers than for the other cohorts.

Discussion

The results of this study demonstrate that within a production system typical of those within temperate Australia, cattle born small grew more slowly after weaning than their larger counterparts, resulting in smaller cattle at any given postnatal age. The results also show that the cattle grown slowly from birth to weaning exhibited incomplete compensation and remained smaller during growth to 30 months of age. Hence, the cattle that underwent restricted growth early in life had smaller carcasses and yielded less beef at 30 months of age. However, when compared at equivalent carcass weights, those cattle restricted in growth from birth to weaning yielded slightly more beef and were leaner than their rapidly grown counterparts, while compositional differences due to birth weight were less apparent. Interactions between sire-genotype and either birth weight or pre-weaning growth were not evident for any of the carcass-, yield-, or beef quality-related variables. Significant interactions mostly related to differences in the magnitude of birth weight and sire-genotypic effects between the cohorts, although an interaction between birth weight and pre-weaning growth was evident for eye muscle area at 380 kg carcass weight.

Few studies have examined long-term consequences of fetal growth on body and carcass characteristics in cattle. Our results show that significantly lower birth weight did not influence indices of carcass fatness beyond differences normally attributable to variation in live or carcass weight at 30 months of age, apart from P8 (rump) fat. At equivalent carcass weight, low birth weight cattle had similar retail yield, fat trim and bone content compared with their high birth weight counterparts, suggesting little overall difference in carcass composition due to birth weight. However, ossification score was higher in low compared with high birth weight calves, suggesting an impact of prenatal growth on degree of calcification of bone (MSA 1999). Similar to our findings, gross compositional differences were not evident in the whole body or the carcass of Hereford steers or heifers grown to 370–400 kg liveweight following restricted or adequate nutrition of their dams from 180 days of pregnancy to parturition with a resultant 22% or 6.8 kg difference in calf birth weight (Tudor 1972; Tudor *et al.* 1980). Research on twin cattle has also demonstrated that, despite significantly lower birth weights and reduced pre-weaning growth (Clarke *et al.* 1994; Hennessy and Wilkins 1997), compositional differences at equivalent slaughter weights or ages are small and not significant, with twins generally having similar or leaner carcasses than singletons (Clarke *et al.* 1994; Gregory *et al.* 1996; Rose and Wilton 1991; Wilkins *et al.* 1994). These findings and those of the present study are in contrast with those in low birth weight sheep that were fatter than those of high birth weight during growth to about 20 kg (Greenwood *et al.* 1998) and 35 kg liveweight (Villette and Theriez 1981).

One of our objectives was to compare carcass and yield characteristics of cattle as divergent in birth weight as was possible within our experimental system. However, it is important to recognise that intrauterine growth retardation resulting in low birth weight has a multifactorial aetiology. Birth weight is a consequence of the net supply of nutrients reaching the fetus, which is influenced by factors including maternal nutrition, parity of the dam, litter size, thermal environment, and fetal and maternal genotype (Greenwood *et al.* 2005; Holland and Odde 1992). Although these factors may affect fetal growth due to the supply of nutrients in maternal blood, they may also influence fetal growth as a result of placental development which is an important regulator of the umbilical supply of nutrients to the fetus (Bell *et al.* 2005). Generally, a prolonged, severe nutritional restriction of cows is required to shift birth weight, and the fetal growth response to maternal nutrition is variable (Cafe *et al*. 2006; Greenwood *et al*. 2005; Holland and Odde 1992). However, within a herd there is typically a wide range of birth weights irrespective of maternal nutrition. For example, among cattle born at GARAS over many years, birth weight ranged from about 15 to 55 kg with an average of 30 to 35 kg (H. Hearnshaw, unpublished data) and the impact of this normal variation in birth weight on subsequent performance is of industrial and biological importance. In this regard, it has previously been suggested that birth weight rather than maternal nutrition influenced postnatal phenotype of sheep grown to 30 months of age (Oliver *et al*. 2002). However, despite failure of the low birth weight calves to catch up in weight during the present study, there was little effect of birth weight on the compositional, yield and beef quality variables measured at about 30 months of age, and the maternal nutritional treatment from which the calves were sourced also had little effect on composition, yield and beef quality.

Although growth of low birth weight cattle was slower than that of high birth weight cattle at all stages of postnatal growth, pre-weaning growth was also likely to have been influenced by the nutritional status of the cows during pregnancy (see Cafe *et al*. 2006). In assessing influences of fetal development on postnatal performance, it was not possible to fully separate consequences of nutrition during pregnancy on the fetus with offspring remaining on their dams to weaning, due to carry-over effects on maternal performance. In a previous study (Tudor and O'Rourke 1980), when low birth weight male calves were artificially-reared to weaning they grew faster than their high birth weight counterparts, whereas the opposite occurred for female calves. In the present study male and female low birth weight calves grown to weaning on their dams grew more slowly. Irrespective, the net effects of maternal nutrition during pregnancy on the calf, which include carry-over affects on lactational performance, remain of practical significance to livestock producers.

Slow growth from birth to weaning resulted in smaller cattle at any given age compared with the high pre-weaning growth cattle, despite some compensatory growth of the slow group during backgrounding. It is generally recognised that severe pre-weaning nutritional restriction limits the capacity of cattle to exhibit compensatory growth and achieve equivalent weight for age in later life, although it remains uncertain whether mature size is compromised (Allden 1970; Berge 1991; Hearnshaw 1997). In reviewing a series of Australian studies on consequences of pre-weaning nutritional systems, Hearnshaw (1997) concluded that compensatory gain occurred most frequently when overall post-weaning growth rates were less than 0.6 kg/day, and when compensation occurs the gains are small. More recently, Hennessy and Morris (2003) found that calves reared slowly (464 g/day) compared with those reared rapidly (872 g/day) from birth to weaning were 37 kg lighter at weaning, but 48 kg lighter following backgrounding owing to a trend towards slower backgrounding growth among the previously restricted cattle. These cattle remained 46 kg lighter at slaughter at 17 months of age compared with those grown more rapidly to weaning.

The present study shows that at an equivalent carcass weight, there was more fat trim, less retail yield, and tended to be less bone in the carcass of the cattle grown rapidly compared with those grown slowly to weaning. This suggests greater fatness at weaning of the rapidly-reared cattle (Cafe *et al*. 2006) contributed to compositional differences at equivalent carcass weights in later life. However, because of failure to fully compensate in weight, the carcasses from light weaners remained smaller and weight of retail beef was lower compared with the heavy weaners at the same age. Earlier studies within pasture-based nutritional systems failed to demonstrate substantial differences in body or carcass composition due to nutrition and growth from birth to weaning (Berge 1991; Hearnshaw 1997; Hennessy *et al*. 2001). These authors concluded that cattle from low pre-weaning nutrition groups generally have less fat than those from high pre-weaning nutrition groups, although if compared at a constant carcass weight, differences in fatness may not be evident. As a result, calves with lower weaning weights take longer to reach carcass specifications than heavier calves. In contrast to the above findings relating to body and carcass composition, severe nutritional restriction to weaning followed by concentrate (high energy) feeding from weaning to slaughter results in increased fatness at the same live and carcass weights compared with cattle well-nourished before weaning (Tudor *et al*. 1980). However, within the same study, cattle restricted or well-nourished to weaning then grown on pasture to the same slaughter weight did not differ in composition.

There were no adverse effects on objective measurements of beef quality due to restricted growth *in utero* that resulted in low birth weights. Similarly, differences in objective measurements of beef quality between the cattle grown slowly and rapidly to weaning were not evident. Consistent with our findings, objective measures of eating quality were not adversely affected by restricted pre-weaning nutritional treatments in earlier studies (Hearnshaw 1997; Hennessy and Morris 2003; Hennessy *et al*. 2001). When they were affected, however, meat of cattle from low nutrition or growth groups was usually more tender than that of high nutrition or high growth groups (Hearnshaw 1997; Hennessy *et al*. 2001). When compared at a constant carcass weight, in about half of these studies the meat quality differences because of nutrition and growth before weaning became non-significant (Hearnshaw 1997).

In the present experiment, interactions between birth weight and pre-weaning growth were not evident for the carcass, yield and beef quality-related variables, apart from eye muscle area at 380 kg carcass weight. However, carcass characteristics were affected by birth weight to varying degrees in the different cohorts, the effects of birth weight generally being smallest within the 2001-born steers. The 2001-born steers gained less weight in the feedlot than the other cohorts, particularly compared with the 2002-born steers. During growth in the feedlot of the 2001-born steers and heifers, periods of high temperatures and humidity lasting several days were experienced regularly during January and February. Although the steers were not weighed during the feeding period, the feed intake and growth rates of the heifers were substantially reduced during these extreme events. The feeding period for the 2001-born steers ended during the hottest of these events which may have contributed to this cohort having greater shear force, compression and cooking loss values, whereas the heifers remained in the feedlot for a further several weeks during which time more moderate weather prevailed. Despite this, ultimate pH was not higher in the 2001-steer cohort and the effect of cohort on beef quality variables was not explained by ultimate pH when included in the analyses as a covariate, suggesting muscle glycogen and lactate production were not lower at slaughter as a result of reduced feed intake in this cohort.

Conclusions

Severe growth retardation of cattle early in life was associated with smaller animals at any given age, resulting in reduced carcass weights and retail beef yield at about 30 months of age. Carcass composition of low and high birth weight calves was similar at 30 months of age. At equivalent carcass weights, however, calves that grew slowly from birth to weaning had carcasses of similar or leaner composition than those grown rapidly within our temperate pasture-based backgrounding system combined with feedlot finishing. Adverse effects of restricted growth during prenatal and/or early-postnatal life on eating quality of beef at 30 months of age were not evident. Furthermore, interactions between growth early in life and sire-genotype were not apparent for any of the carcass, yield or beef quality traits.

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References

Allden WG (1970) The effects of nutritional deprivation on the subsequent productivity of sheep and cattle. *Nutrition Abstracts and Reviews* **40**, 1167–1184.

AUS-MEAT (1998) 'Handbook of Australian meat.' (AUS-MEAT Ltd: Brisbane)

Bell AW, Greenwood PL, Ehrhardt RA (2005) Regulation of metabolism and growth during prenatal life. In 'Biology of metabolism in growing animals'. (Eds DG Burrin, HJ Mersmann) pp. 3–34. (Elsevier: Amsterdam)

Berge P (1991) Long-term effects of feeding during calfhood on subsequent performance of beef cattle (a review). *Livestock Production Science* **28**, 179–201. doi:10.1016/0301-6226(91)90142-D

Cafe LM, Hennessy DW, Hearnshaw H, Morris SG, Greenwood PL (2006) Influences of nutrition during pregnancy and lactation on birth weights and growth to weaning of calves sired by Piedmontese or Wagyu bulls. *Australian Journal of Experimental Agriculture* **46**, 245–255.

Clarke AJ, Cummins LJ, Wilkins JF, Hennessy DW, Andrews CM, Makings BJ (1994) Post weaning growth of twin cattle born at Hamilton and Grafton. *Proceedings of the Australian Society of Animal Production* **20**, 34–35.

Greenwood PL, Hunt AS, Hermanson JW, Bell AW (1998) Effects of birth weight and postnatal nutrition on neonatal sheep: I. Body growth and composition, and some aspects of energetic efficiency. *Journal of Animal Science* **76**, 2354–2367.

Greenwood PL, Cafe LM, Hearnshaw H, Hennessy DW (2005) Consequences of nutrition and growth retardation early in life for growth and composition of cattle and eating quality of beef. *Recent Advances in Animal Nutrition in Australia* **15**, 183–195.

Gregory KE, Echternkamp SE, Cundiff LV (1996) Effects of twinning on dystocia, calf survival, calf growth, carcass traits and cow productivity. *Journal of Animal Science* **74**, 1223–1233.

Hearnshaw H (1997) Effect of pre-weaning nutrition on post-weaning growth, carcase and meat quality traits. In 'Growth and development of cattle. Proceedings of the growth and development workshop'. (Eds DW Hennessy, SR McLennan, VH Oddy) pp. 59–67. (Cooperative Research Centre for Cattle and Beef Quality: Armidale)

Hennessy DW, Morris SG (2003) Effect of a preweaning growth restriction on the subsequent growth and meat quality of yearling steers and heifers. *Australian Journal of Experimental Agriculture* **43**, 335–341. doi:10.1071/EA02072

Hennessy DW, Wilkins JF (1997) The nutrition of single and twin suckled calves and their growth-12 months post weaning. In 'Growth and development of cattle. Proceedings of the growth and development workshop'. (Eds DW Hennessy, SR McLennan, VH Oddy) pp. 45–47. (Cooperative Research Centre for Cattle and Beef Quality: Armidale)

Hennessy DW, Morris SG, Allingham PG (2001) Improving the pre-weaning nutrition of calves by supplementation of the cow and/or the calf while grazing low quality pastures. 2. Calf growth, carcass yield and eating quality. *Australian Journal of Experimental Agriculture* **41**, 715–724. doi:10.1071/EA00153

Holland MD, Odde KG (1992) Factors affecting calf birth weight: a review. *Theriogenology* **38**, 769–798. doi:10.1016/0093-691X(92)90155-K

MSA (1999) 'Grading for eating quality — Development of the Meat Standards Australia Grading System. Vol. 1.' (Meat Standards Australia: Newstead)

Oliver MH, Breier BH, Gluckman PD, Harding JE (2002) Birth weight rather than maternal nutrition influences glucose tolerance, blood pressure, and IGF-I levels in sheep. *Pediatric Research* **52**, 516–524. doi:10.1203/01.PDR.0000028852.63989.11

Payne RW, Arnold GM (1997) 'Genstat 5 Release 4.1. Genstat 5 Committee, National Algorithms Group.' (Clarendon Press: Oxford)

Perry D, Thompson JM (2005) The effect of growth rate during backgrounding and finishing on meat quality traits in beef cattle *Meat Science* **69**, 691–702. doi:10.1016/j.meatsci.2004.10.020

Perry D, Shorthose WR, Ferguson DM, Thompson JM (2001) Methods used in the CRC program for the determination of carcass yield and beef quality. *Australian Journal of Experimental Agriculture* **41**, 953–957. doi:10.1071/EA00092

Robinson DL, Oddy VH, Dicker RW, McPhee MJ (2001) Post-weaning growth of cattle in Northern New South Wales 3.Carry-over effects on finishing, carcass characteristics and intramuscular fat. *Australian Journal of Experimental Agriculture* **41**, 1041–1049. doi:10.1071/EA00093

de Rose EP, Wilton JW (1991) Productivity and profitability of twin births in beef cattle. *Journal of Animal Science* **69**, 3085–3093.

Tudor GD (1972) The effect of pre- and post-natal nutrition on the growth of beef cattle. I. The effect of nutrition and parity of the dam on calf birth weight. *Australian Journal of Agricultural Research* **23**, 389–395. doi:10.1071/AR9720389

Tudor GD, O'Rourke PK (1980) The effect of pre- and post-natal nutrition on the growth of beef cattle. II. The effect of severe restriction in early postnatal life on growth and feed efficiency during recovery. *Australian Journal of Agricultural Research* **31**, 179–189. doi:10.1071/AR9800179

Tudor GD, Utting DW, O'Rourke PK (1980) The effect of pre- and post-natal nutrition on the growth of beef cattle. III. The effect of severe restriction in early postnatal life on the development of the body components and chemical composition. *Australian Journal of Agricultural Research* **31**, 191–204. doi:10.1071/AR9800191

Villette Y, Theriez M (1981) Effect of birth weight on lamb performances. II. Carcass and chemical composition of lambs slaughtered at the same weight. *Annales de Zootechnie* **30**, 169–182.

Wilkins JF, Hennessy DW, Farquharson RJ (1994) Twinning in beef cattle. Roles of nutrition and early weaning in herds of high calving rate. Final Report to Meat Research Corporation. NSW Agriculture, Grafton.

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