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1 **Characterisation of beef production systems and their effects on**
2 **carcass and meat quality traits of Piemontese young bulls**

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13 **Abstract**

14 Using the Piemontese breed as a case study, we characterised beef production systems within
15 the EU classification, and investigated their effects on carcass and meat quality traits. The
16 research involved 1,327 young bulls fattened on 115 farms. The production systems identified by
17 hierarchical cluster analysis were: traditional (restricted feeding and either tie-stalls or loose-
18 housing), modern breeders and fatteners and specialised fatteners (the last two were divided in
19 those using or not using total mixed rations). Despite the large variability in management
20 techniques within production systems, production systems affected ($P < 0.05$) farm size, animal
21 density, environmental scoring, diet, slaughter age and all carcass traits except weight. Lightness
22 (L^*) of *Longissimus thoracis* was the only meat quality trait affected ($P < 0.05$), with values
23 greater in the traditional tie-stall system (+0.9 L^*). Given the very limited effect of production
24 systems on meat quality traits, factors related to individual animals within farms, such as
25 genetics, should be considered for their improvement.

26 **Keywords:** meat colour traits; lightness; tenderness; cooking losses; Piemontese.

27 **1. Introduction**

28 A study by the European Commission (2011) on the structure of EU beef farms identified three
29 main specialised beef cattle production systems. Suckler cow farmers who produce calves to be sold to
30 other farms for fattening were classified as “breeders”, farmers who fatten calves born on their farms
31 were classified as “breeders and fatteners” (B&F), and farmers who purchase weanlings to fatten in
32 their farms were classified as “specialised fatteners”.

33 According to a Farm Accountancy Data Network (FADN) survey, the large majority of European
34 suckler cows are raised in specialised beef operations: 35% by beef breeders and 39% by beef B&F,
35 with the remaining 26% reared on mixed dairy-beef cattle or sheep-beef cattle farms (European
36 Commission, 2011). Only around 50% of male cattle sold at between 1 and 2 years of age are raised on
37 specialised beef farms with specialised fatteners (35%) predominating over B&F (17%). The
38 distribution of suckler cows across farming systems in Italy is similar to that of the EU, whereas
39 specialised beef fatteners have by far the largest share of male cattle marketed at between 1 and 2 years
40 of age (71%) (European Commission, 2011).

41 In Italy, Piemonte is a suitable case study region because it is the only one that appears on the list of
42 the most important European regions for each of the three beef livestock systems classified by the EU:
43 breeders, B&F and specialised fatteners (European Commission, 2011). Moreover, Piemonte, along
44 with Belgium, obtains the highest prices per male sold, due to their double-muscled breeds: Piemontese
45 and Belgian Blue, respectively.

46 The Piemontese (Piedmontese) is the most important Italian beef breed, with an overall population
47 of 330,000, including 153,000 cows (Veterinary Information System, 2017), 90% of which are
48 registered in the Italian Piemontese Herd Book (ANABORAPI, 2017).

49 The beef farming systems in Piemonte are evolving away from very traditional practices (tied
50 animals fed mainly hay and restricted amount of concentrates) to modern ones (loose-housed animals,

51 *ad libitum* feeding and use of total mixed rations [TMR]), and the different systems now coexist
52 (Sgoifo Rossi, Pastorello, Caprarotta, & Compiani, 2011).

53 A few studies have looked at the effects of production system or feeding techniques during the
54 fattening period on carcass and meat quality traits (Daza, Rey, Lopez-Carrasco, & Lopez-Bote, 2014;
55 Avilés, Martínez, Domenech, & Peña, 2015). Other studies have also focused on the possible impact of
56 type of animal management before the fattening period on production and meat quality (Dannenberger,
57 Nuernberg, Nuernberg, & Ender, 2006; Guerrero et al., 2013). However, most of the studies
58 investigated very general effects, such as intensive *vs* extensive systems or concentrate *vs* forage
59 feeding.

60 More recent studies highlighted that individual information on rearing conditions of animals can be
61 exploited with the aim of identifying management techniques affecting carcass and meat quality traits
62 (Gagaoua, Monteils, Couvreur, & Picard, 2017) or to develop predictive models for the same traits
63 (Soulat, Picard, Léger, & Monteils, 2016; Soulat, Picard, Léger, & Monteils, 2018).

64 Currently no detailed analyses of the fattening systems classified as B&F and specialised fatteners,
65 especially in relation to their effects on animal performance and meat quality traits, and particularly
66 with regard to hypertrophic breeds exist.

67 The aim of this study, therefore, was to characterise the beef production systems and assess their
68 effects on carcass and meat quality traits using Piemontese breed as a case study.

69 This knowledge is important for: making a sound economic and technical comparison of the
70 different systems, for predicting future trends in carcass and meat quality trait at population level in the
71 light of the evolution of beef production systems, and for setting future selection goals for genetic
72 improvement of the breed.

73 **2. Material and Methods**

74 This study is part of the “Qualipiem” project, which is aimed at analysing the phenotypic and
75 genetic sources of variation in meat quality traits in the Piemontese breed and at proposing innovative
76 selection strategies for their improvement.

77 **2.1. Farm sampling and data collection**

78 Information on the farms was collected through an interview-based field survey. A total of 115
79 farms in the Piedmont region (north-west Italy) were selected according to the following criteria: they
80 were interested in the aims of the research, their cows were registered in the Piemontese Herd Book
81 (only for B&F farms), they were using, at least in part, artificial insemination, and were delivering their
82 slaughter animals to the largest local cooperative slaughterhouse. Trained technicians visited each farm
83 selected and assisted the farmer in filling out a questionnaire designed to elicit information on farm size
84 (land area in ha and number of fattened animals per year), management practices and animal welfare.
85 Information about management practices included: beef production system (B&F *vs* specialised
86 fatteners), housing system (tie-stalls *vs* loose-housing), feed supply (restricted *vs ad libitum*), feed
87 distribution (TMR *vs* separate distribution of concentrates and forage) and feed composition (as
88 proportions in rations). In order to obtain chemical composition of feeding, analytical information of
89 purchased commercial feeding was registered, whereas for farm produced feedstuffs, chemical
90 composition of feeds used was derived from the chemical analysis of each feed ingredient (Sauvant et
91 al. 2004). The animal welfare information included space allowance (m² per head) and assessments of
92 building adequacy, cleanliness, aeration, water availability and animal docility on a scale of 1 to 3
93 (1=insufficient, 2=sufficient, 3=good). Farms were also given an overall evaluation by averaging the
94 above-mentioned scores with the exception of animal docility.

95 The questionnaire was tested before its application for data collection on a sample of farms during
96 the training of technicians.

97 **2.2 Animals and beef sampling**

98 The study was carried out sampling 1,327 Piemontese young bulls progeny of 204 A.I. purebred
99 sires and 1,286 dams, all registered in the Italian Piemontese Herd Book. All the animals were
100 slaughtered at the same commercial abattoir (Operti, Centallo (CN), 12044, Italy) from April 2015 to
101 February 2017. The young bulls were stunned using captive-bolt pistol prior to exsanguination and
102 dressed according to standard commercial practices. Slaughtering was performed in compliance with
103 the Italian welfare regulations and respecting EU regulations (Council Regulation (EC) No.
104 1099/2009). After slaughter, hot carcass weight (CW) and carcass conformation class according to the
105 EU linear grading system (Commission of the European Communities 1982) were recorded. In order to
106 better differentiate carcass conformation, the six main grades (S, E, U, R, O, P, from best to worst)
107 were further divided into three subclasses (+, = or -) **as allowed by European Union regulations (Hickey,**
108 **Keane, Kenny, Cromie, & Veerkamp, 2007)**. Prior to statistical analysis, the categories of carcass
109 conformation were rearranged into numerical scores (EUS) ranging from 1, corresponding to class “P-
110 ”, to 18, corresponding to class “S+”. Fatness was not scored in this study as the carcasses of double-
111 muscled breeds are known to be lean and hence exhibit little variation in fatness.

112 Age at slaughter (AS) was calculated from date of birth to date of slaughter. As individual live
113 weights of animals were not available, daily carcass gain (CDG) calculated as the ratio of carcass
114 weight to age at slaughter, was used as measure of young bulls growth rate (Juniper et al., 2005;
115 Boukha et al., 2011).

116 The carcasses were not electrically stimulated and they were chilled at 4 °C until twenty-four hours
117 post-mortem. Twenty-four hours after slaughter, individual samples (4.0 cm thick) of the *Longissimus*
118 *thoracis* (LT) muscle were collected from between the fifth and sixth thoracic vertebrae. The muscle
119 and the excision area were chosen because displayed during the routine slaughterhouse procedures of
120 subdivision of half-carcasses into quarters according to pistol cutting.

121 The beef samples were scanned with a HP Scanjet 5590 Digital Flatbed Scanner (Hewlett-Packard;
122 Palo Alto, California) to obtain images for subsequent measurement of the rib eye area (REA, cm²). For

123 image calibration, a ruler marked in centimeters was scanned with meat samples. Then, samples were
124 individually vacuum packed and transferred under refrigerated conditions to the laboratory, where they
125 were stored in a chilling room at 4°C for 7 days, after which meat quality traits were measured.

126 **2.3. Analysis of meat quality traits**

127 After ageing (7 days), purge losses (PL) were determined according to the following procedure: the
128 steaks were first weighed in the bag (packaged weight, W1), then after removal from the bag
129 (unpacked weight, W3), and then the bag was rinsed, dried and weighed (bag weight, W2). PL (%)
130 was calculated as $(W1-W2-W3)/(W1-W2) \times 100$.

131 Ultimate pH (7 days) was measured with a portable Crison pH-meter PH 25+ (Crison Instruments
132 S.A.; Alella, Barcelona) equipped with a glass electrode Crison 52 32 suitable for meat penetration and
133 an automatic temperature compensator. Before analysis, the pH-meter was calibrated using standard
134 buffers (pH 4.0 and 7.0). The electrodes were inserted approximately 1 cm into the muscle (Boccard et
135 al. 1981).

136 The digital images of the samples were processed with the Image Pro Plus 4.5.1. software (Media
137 Cybernetics, 2001) in order to measure the rib eye area (REA, cm²). Before each measurement, the
138 image was calibrated with a ruler. The surrounding edge of the sample was automatically traced.
139 However, a manual trace by the operator was added when errors in the automatically trace occurred.
140 Only one experienced operator performed all the measurements.

141 Colour was measured with a Konica Minolta CR-331C colourimeter (Konica Minolta Sensing
142 Americas, Inc; Ramsey, New Jersey) on the freshly-cut surface of each steak after blooming for 1 h at
143 4°C. The CR-331C colourimeter features 45° circumferential illumination/0° viewing geometry, a
144 Ø25mm measuring area and 2° standard observers. The instrument was calibrated on its own white
145 reference tile supplied by the manufacturer and set with the illuminant D65 (colour temperature 6500
146 K), which represents average daylight. CIELAB coordinates (CIE 1976), lightness (L*), redness (a*)

147 and yellowness (b^*) were recorded, and hue angle (h^*) was calculated as $h^* = \tan^{-1} (b^*/a^*)$, Chroma
148 (C^*) as $C^* = (a^{*2} + b^{*2})^{0.5}$. Three random readings were taken at different locations on the meat surface
149 and averaged.

150 After colour measurements had been taken, cooking losses (CL) were determined. Each steak was
151 sealed in a polyethylene bag and cooked in a water bath preheated at 75°C to an internal temperature of
152 70°C. The cooking temperature was monitored with a thermometer inserted into the geometric centre
153 of the steak. When the set temperature was reached, the steak was removed from the water bath and
154 cooled for 30 min under tap water to prevent further cooking. It was then removed from the bag,
155 blotted and reweighed (Honikel, 1998). Cooking Losses (%) were calculated as the weight difference
156 between the raw and the cooked samples as percentage of the weight of the raw meat sample. The
157 steaks used to determine cooking losses were also used for the Warner Bratzler shear force (WBSF) test
158 after overnight chilling at 4°C. Six cylindrical cores of cooked meat 1.27 cm in diameter, taken parallel
159 to the muscle fibres were sheared perpendicularly to the longitudinal orientation of the muscle fibres
160 with a V shaped Warner-Bratzler cutting blade fitted to an Instron 5543 Universal Testing Machine
161 (Instron; Norwood, Massachusetts). WBSF was measured as the maximum force (Newtons) required to
162 shear the cylindrical core at a crosshead speed of 200 mm per min (A.M.S.A., 2015).

163 **2.4. Statistical analyses**

164 **2.4.1. Identification and characterisation of beef production systems**

165 Recent studies (Gagaoua et al., 2017; Soulat et al., 2018) implemented innovative statistical
166 methodologies combining factorial or principal component with cluster analyses for the study of meat
167 quality traits. These methods were able to efficiently categorize animals into management groups and
168 proved to be particularly useful when a very high number of quantitative or qualitative variables were
169 involved. In the present study, the limited number of parameters related to structural and technical

170 features of the investigated farms and the categorical nature of these parameters suggested the authors
171 to perform an agglomerative hierarchical cluster analysis.

172 The systems were then classified by cluster analysis (Lin & Lin, 1994) on the basis of the following
173 four variables: beef production system (B&F *vs* specialised fatteners), housing system (tie-stalls *vs*
174 loose-housing), feed supply (restricted *vs ad libitum*) and feed distribution (TMR *vs* separate
175 distribution of concentrates and forage).

176 A dissimilarity matrix was created with the SAS DISTANCE procedure (2013) using the general
177 dissimilarity coefficient of Gower (1971), an appropriate index for handling nominal, ordinal and
178 (a)symmetric binary data. It was then analysed with the SAS CLUSTER procedure (2013) to create
179 agglomerative hierarchical clusters using Ward's minimum variance method (Murtagh & Legendre,
180 2014). The optimal number of clusters was chosen on the basis of visual inspection, pseudo T-squared
181 (quantification of the difference in the ratio of between-cluster to within-cluster variance by merging
182 clusters), semi-partial R^2 statistics and validate by calculating average silhouette width (S_i) criterion
183 (Rousseeuw, 1987; Gagaoua, Picard, Soulat & Monteils, 2018).

184 Land area, number of fattened animals per year, number of fattened animals per ha, and animal
185 welfare traits (space allowance, building, cleanliness, aeration, water supply, animal docility and
186 overall environmental evaluations) were subjected to a one-way ANOVA with the identified production
187 systems as the source of variation. Orthogonal contrasts based on the effects of production system were
188 used to compare general management strategies across the identified systems (tie-stalls *vs* all loose-
189 housing; within loose-housing: traditional restricted *vs* modern *ad libitum* feeding; within modern
190 systems: B&F *vs* fatteners, TMR *vs* separated diet and their interaction).

191 **2.4.2. Statistical analysis of carcass and meat quality traits**

192 The effects of production system on carcass and meat quality traits were assessed on the basis of
193 individual data from the 1,327 young bulls sampled after removing observations falling outside the

194 range of 3 standard deviations from the mean for each trait. Age at slaughter and carcass traits were
195 analysed with the SAS MIXED procedure (2013) adopting the following statistical model:

196

$$197 \quad y = \text{birth season} + \text{parity of dam} + \text{production system} + \text{farm}(\text{production system}) + \text{batch} + \varepsilon$$

198

199 where y represents the observation of each of the investigated traits; birth season (4 classes: January-
200 March, April-June, July-September, October-December), parity of dam (4 classes: 1st, 2nd, 3rd-8th,
201 >8) and production system are all fixed effects, farm is the random effect of the fattening farm nested
202 within production system (98 levels), batch is the random effect of the day of slaughter (117 levels) and
203 ε is the random residual term. Farms, batch and ε were assumed to be normally and independently
204 distributed $\sim N(0, \sigma^2)$. A minimum cell size of 3 observations was required for both the batch and farm
205 effects.

206 The fixed effect of carcass weight, (5 classes: <350kg, 350-400kg, 401-450kg, 451-500kg, >500kg)
207 was added to the previous model for the analysis of meat quality traits.

208 The effects of different management strategies were evaluated with orthogonal contrasts, whereas
209 comparisons of the least square means of the other fixed effects were performed with a Tukey-Kramer
210 test ($P < 0.05$).

211 **3. Results**

212 **3.1. Beef production systems**

213 Six clearly recognizable production systems with a good assignment of farms to groups (best
214 silhouette width criterion $S_i=0.73$) were identified from the cluster analysis (Table 1). Farms
215 characterised by restricted feeding without the use of TMR were classified as traditional systems, with
216 a distinction made between tie-stall and loose-housing of animals. Modern farms, characterised by

217 loose-housed animals fed *ad libitum*, were divided into B&F or specialised fatteners, each further
218 differentiated according to whether not they used TMR.

219 Traditional farms represented almost 40% of the units surveyed, followed by modern fatteners
220 (33%) and B&F (28%). Nevertheless, almost 41% of the animals sampled came from modern
221 specialised fatteners, 32% from B&F systems and only 27% from traditional farms, reflecting the
222 smaller size of the latter. The distribution of the farms across the criteria used for the cluster analysis
223 allowed us to describe the main characteristics of the beef production systems identified. In half of the
224 farms in the study, cow-calf and fattening operations were integrated, and loose-housing predominated
225 over tie-stalls (77% of farms). The majority of farms (66%) adopted modern *ad libitum* distribution of
226 feed, but only 30% of farms used TMR, probably due to farm size.

227 Comparison of farm size traits across the identified production systems is shown in Table 2. On
228 average, the farms were 39 ha in size, fattened 82 animals per year with a very large variation across
229 herds, and allocated around 5.00 m² of space to each fattening animal. The production system affected
230 ($P < 0.05$) all the traits investigated. Traditional farms with tie-stalls were the smallest ($P < 0.05$), with
231 an average size of 27.4 ha. Within the systems adopting loose-housing, traditional systems with
232 restricted feeding were smaller (32.1 ha) ($P < 0.05$) than modern ones. Farms using TMR were the
233 largest ($P < 0.01$), with an average of 51.5 ha for B&F, 58.7 ha for fatteners. As expected, traditional
234 farms with tied animals allocated the least space ($P < 0.01$) to fattening animals at 2.00 m² per head.
235 Average space allowance for loose animals was lower ($P < 0.01$) in specialised fattener systems than in
236 B&F systems, reflecting the former's more intensive management and higher ($P < 0.01$) animal density.
237 As a consequence of purchasing calves from other farms, specialised fatteners produced about three
238 times more slaughter animals per year than B&F, despite their similar size in terms of land area.

239 Table 3 shows the effects of production system on some of the indices of animal welfare and
240 environmental conditions. Traditional farms with tie-stalls were the worst overall, with lower ($P <$
241 0.05) scores for all the traits evaluated (not significant only for animal docility). Although the two

242 traditional systems shared certain management features, those with loose-housing were more similar in
243 structural traits to the modern systems. Among the modern systems, overall conditions were better ($P <$
244 0.01) in those using TMR, mainly as a consequence of more modern buildings.

245 Diet compositions in the different production systems are compared in Table 4. Ground corn was
246 the main feed in every system, accounting for between 30 and 40% of the concentrate mix or TMR
247 supplied to fattening animals. Corn silage was very seldom part of the diet in the systems analysed, and
248 even when it was detected (11 of the 115 farms), as in some TMR specialised fattener units, it was
249 never the main component of the diet. Ear corn silage was widely used in TMR systems ($P < 0.01$) and
250 was an important part of the diet, especially in B&F units. Furthermore, in TMR systems, individual
251 feed ingredients were far more widely used than purchased compound feeds ($P < 0.01$). In all the other
252 systems, the use of commercial compound feed was common, with average proportions in the diets
253 ranging from 30% (traditional, pens) to 49% (B&F, without TMR). In the traditional and modern
254 systems that didn't use TMR, hay distributed *ad libitum* was always used as forage, while a mixture of
255 hay and wheat straw was included in the feed in both TMR systems.

256 Table 5 shows the estimated chemical composition of the concentrates supplied in the different beef
257 production systems, expressed as percentage of raw feed. On average, concentrates contained 13%
258 crude protein (CP), 6% crude fibre (CF), 4% ether extract (EE) and 5% ashes (AS). The CP content
259 differed ($P < 0.01$) across production systems, with the lowest proportions found on farms using TMR,
260 probably due to ear corn silage being a substantial component of the diet.

261 **3.2. Carcass and meat quality traits**

262 Descriptive statistics, the ANOVA results and the effects of beef production system on the carcass
263 traits of Piemontese young bulls are presented in Table 6. The average carcass weight of the
264 Piemontese young bulls sampled was 438.1 (± 43.6) kg, while the average age at slaughter was 540.9

265 (± 63.2) days, giving an average daily carcass gain of 0.818 (± 0.107) kg/d. Average EUS was 14.66,
266 corresponding to an average evaluation approaching “E+” in the EU linear grading system.

267 The effect of individual farm within production system explained a proportion of the total variance
268 that varied greatly according to the trait considered, from only about one twentieth in the case of the rib
269 eye area, one tenth for EUS, a quarter for carcass weight and daily carcass gain, to about half for age at
270 slaughter (Table 6), highlighting that the large variability in management techniques still exists even
271 within a given production system. The results show that the batch effect, i.e. animals slaughtered on the
272 same day, explained a much smaller amount of variance than farm, ranging from 4.7% for daily carcass
273 gain to 17.6% for the rib eye area. In the case of the latter trait, it is possible there was an influence of
274 slaughterhouse operator during the sample collection.

275 Production traits (age at slaughter and daily carcass gain), but not carcass quality (EUS and rib eye
276 area), were affected by the young bulls' birth season ($P < 0.01$) (results were most favourable in the
277 January/March season, the least in the April/June season) and the parity of their dam ($P < 0.01$) (the
278 most favourable results were obtained for 3rd-8th parity class).

279 Production system affected age at slaughter ($P < 0.05$), carcass daily gain ($P < 0.01$) and SEUROP
280 ($P < 0.05$). The results for the traditional beef system with tied animals, in particular, were much worse
281 than all the systems with loose-housed animals: tied young bulls grew more slowly ($P < 0.01$) (-0.070
282 kg/d), over a longer ($P < 0.01$) fattening period (+40 d) to reach a similar weight (-10 kg), and their
283 carcasses had lower ($P < 0.01$) muscularity scores (-0.64) and less ($P < 0.05$) rib-eye area (-3.2 cm²).
284 The production traits of the 5 beef systems rearing loose-housed animals did not differ much, except
285 that the rib-eye of carcasses produced on modern B&F farms had larger ($P < 0.05$) cross-sectional area
286 than those produced by specialised fatteners (+3.2 cm²).

287 As shown in Tables 7 and 8, colour and meat quality traits were consistently affected by batch,
288 which explained an average of around 30% of total variance, ranging from 14% for PL to 63% for pH,
289 the latter trait characterised by little overall variability. The amount of variance explained by the effect

290 of farm within beef system, instead, was almost negligible, with L* and PL having the highest values at
291 around 7% of total variance.

292 Colour traits, pH and CL were not affected by the young bulls' season of birth nor by the parity of
293 their dams, although both of them had a moderate ($P < 0.05$) influence on PL and the former on shear
294 force ($P < 0.05$).

295 The class of carcass weight was a very important source of variation in all meat quality traits, with
296 the only exception of shear force as the LSMs of the heaviest class were always higher ($P < 0.05$) than
297 those of the lightest.

298 After taking into account the effects of all the other sources of variation included in the model, beef
299 production system was found to have very little influence on the quality traits. In fact, the differences
300 between the production systems were significant only for one of the colour traits, L*. The traditional
301 tie-stall system produces meat with the highest ($P < 0.05$) L* value, probably due to the animals' lack of
302 physical activity, underlined by the contrast between tie-stalls and all loose-housing systems. Feeding
303 was also found to influence ($P < 0.05$) the L* of meat, which was darker from animals fed TMR than
304 from animals fed separated concentrates and hay. We did not find production system to have any
305 influence on pH, shear force and the two water loss traits, PL and CL.

306 **4. Discussion**

307 **4.1. Beef production systems**

308 Few previous studies have directed attention to characterising the farming systems used in beef
309 production. Some recent studies are focused on geographical areas and production techniques far from
310 EU conditions (Asem-Hiablie, Rotz, Stout, & Fisher, 2017; Asem-Hiablie, Rotz, Sandlin, Sandlin, &
311 Stout, 2018; Cavalcante et al., 2018). The use of the Piemontese breed as a case study, allowed to
312 analyse in detail the beef production system in an European context. Due to the characteristics of the
313 present research, the obtained results could be of interest also for other European beef breeds

314 characterised by lean carcasses and for European production systems characterised by intensive
315 fattening.

316 The beef production systems characterised in the present investigation on the basis of a combination
317 of operation cycle, housing and feeding techniques, showed that traditionally managed farms still
318 coexist with more advanced units using modern technologies. B&F and specialised fattener systems are
319 equally represented in our study in terms of both farms and animals. The loose-housing system has
320 been widely adopted, substantiating Sgoifo Rossi et al.'s (2011) findings, which showed an increase in
321 this management system since a previous study on Piemontese breed carried out by Destefanis et al.
322 (2005), who reported an incidence of 56.2%. The structural investments needed for traditional farms
323 with pens to move from tie-stalls to loose-housing allows them to provide their animals with better
324 environmental conditions. Changes in feeding strategies also reveal a tendency towards modernisation:
325 *ad libitum* increased from 46% (Destefanis et al., 2005) to 66% of feed supply system, and TMR was
326 used on 30% of farms against negligible use in previous studies. More advanced type of feed, such as
327 TMR, go hand in hand with a management technique characterised by modern technology and
328 structures. Although fatteners using TMR had the highest density of animals among all the loose-
329 housing systems, their results were the best in most of the subjective environmental evaluations.

330 Concerning feeding, we were unable to compute the exact nutritional composition of the rations, as
331 we did not have any information on the amount of hay and straw distributed *ad libitum* to fattening
332 animals. However, we were able to calculate the nutritional composition of the concentrate mix by
333 deducting the amount of hay and straw from TMR. The average dietary content of crude protein (CP)
334 varied little among production systems, ranging from 133 to 144 g/kg dry matter (DM).

335 Boucqué, Fiems, Cottyn, & Buysse (1984) suggested that a CP content exceeding 140 g/kg DM was
336 required for Belgian Blue young bulls. De Campeneere, Fiems, Cottyn, & Boucqué (1999) suggested a
337 CP concentration decreasing from 163 to 120 g CP/kg of dry matter intake (DMI) for the same breed at
338 different stages of life as a function of the animal's body weight. Reducing the CP content in the diet of

339 purebred Piemontese young bulls from 145 g/kg to 108 g/kg of DMI across the whole fattening cycle
340 was not found to affect growth performance (Schiavon, Tagliapietra, Dal Maso, Bailoni, & Bittante,
341 2010), nor carcass and meat quality traits (Schiavon et al., 2011), but it improved the efficiency of
342 dietary nitrogen use (Schiavon, Tagliapietra, Dalla Montà, Cecchinato, & Bittante, 2012).

343 The crude fibre content of the concentrate mix was also relatively low ($6.0\pm 1.6\%$ as fed), especially
344 when the modest level of corn silage and dry roughage included in the rations compared with other
345 beef systems was considered (Cozzi, Mazzenga, Contiero, & Burato, 2008). In assessing the high
346 energy content of the diets used in all the beef production systems studied here, consideration should be
347 given to the very low fat deposition ability of all double-muscled breeds (Fiems, 2012) and the
348 difficulty in reaching the minimal level of carcass fatness required by the beef market.

349 **4.2. Carcass and meat quality traits**

350 Piemontese cattle are highly specialised for beef production as they are double-muscled, a specific
351 mutation of the myostatin gene (*mh*) located on Chromosome 2 (Grobet et al., 1998), which is almost
352 fixed in this population. Moreover, this breed is heavily selected for improvement in growth rate and
353 carcass conformation (Albera, Mantovani, Bittante, Groen, & Carnier, 2001) and also, unlike the
354 Belgian Blue, for ease of calving (Kizilkaya et al., 2003). Like other double-muscled breeds,
355 Piemontese cattle have large muscular masses and low fat deposition, and reduced incidence of the
356 skeleton, lower feed intake and better feed conversion (Fiems, 2012) than non-double-muscled
357 specialised beef breeds.

358 Average values for carcass traits were consistent with those reported in a previous study on the
359 carcass and meat quality traits of Piemontese young bulls (Boukha et al., 2011). In our study, carcass
360 weight was slightly higher, as was the age at slaughter, hence average daily carcass gain was very
361 similar. The average EUS we obtained, close to the “E+” class, is greater than the “E-” average score
362 reported in the aforementioned study (Boukha et al., 2011) and also had slightly lower variability.

363 There is very little information in the literature on the rib eye area of purebred Piemontese animals. The
364 average value of the rib eye area obtained in the present study was comparable to those reported by
365 Tatum, Gronewald, Seideman, & Lamm (1990) and by Wheeler, Cundiff, Koch, & Crouse (1996) for
366 crossbred Piemontese steers.

367 The quality of meat from double-muscled Piemontese animals meets the requirements of Italian
368 consumers. It has higher water and protein contents and lower levels of intramuscular fat, usually about
369 1% (Barge, Brugiapaglia, Destefanis, & Mazzocco, 1993), than meat from conventional animals while
370 the low collagen content is responsible for its greater tenderness (Destefanis, Barge, & Brugiapaglia,
371 1994). Meat from the Piemontese young bulls and heifers is also in the European Union's register of
372 protected geographical indications (PGI) as “Vitelloni Piemontesi della Coscia” (Reg. no. 703/2017,
373 5th April 2017).

374 The results on meat quality in this study also largely agreed with those reported in previous studies
375 on the Piemontese breed (Boukha et al., 2011; Cecchinato, De Marchi, Penasa, Albera, & Bittante,
376 2011). As in those studies, pH values displayed very small variability and did not exceed 5.87, the
377 value proposed by Page, Wulf, & Schwotzer (2001) as the approximate cut-off between normal and
378 dark-cutting beef carcasses. The average pH value obtained in this study was also very close to those
379 reported by Boukha et al. (2011) for Piemontese young bulls and by Fiems, De Campeneere, Van
380 Caelenbergh, De Boever, & Vanacker (2003) for Belgian Blue bulls.

381 Meat colour results were very similar to those found by Page et al. (2001) from 1,062 beef
382 carcasses, both in terms of average values and variability, but differed from those reported by Boukha
383 et al. (2011) probably due to the different instruments used for colour detection. We obtained lower
384 average values for CL and shear force compared with Destefanis, Brugiapaglia, Barge, & Lazzaroni's
385 (2003) results for Piemontese young bulls and steers, but we found greater variability in both traits, as
386 expected when comparing a large field survey with an experimental trial.

387 **4.3. Effects of carcass weight on meat quality traits**

388 In general, our results revealed a marked effect of carcass weight on colour and meat quality traits.
389 It should be noted that carcass weight is not to be taken as resulting from prolonging or shortening the
390 fattening period of a given young bull, but is rather a measure of young bulls heavier or lighter
391 carcasses. Carcass weight was related to age at slaughter ($r = +0.24$), but especially to daily carcass
392 gain ($r = +0.56$), and probably also to dressing percentage and fat deposition. Indeed, young bulls with
393 higher daily carcass gains were of a lower age at slaughter and reached commercial maturity faster.

394 The heavier carcasses were associated with brighter meat resulting from a combination of higher
395 values in all the three colour coordinates. The relationship between carcass weight and L^* was reported
396 by Murray (1989), who analysed 7,695 beef carcasses produced in field conditions and found that
397 carcass weight was inversely related to the incidence of dark meat: carcasses weighing less than 272 kg
398 had twice the incidence of dark meat (5.1%) than those weighing more than 318 kg (2.6%).
399 Furthermore, in a study on Charolais, Limousin and dairy-cross animals, Craigie et al. (2010) found
400 that a^* and b^* were associated with carcass weight.

401 Irrespective of the production system, carcass weight also had a strong effect on most of the other
402 quality traits. We found a significant effect of carcass weight class on pH, but we do not expect any
403 practical implications as the variability in this trait was very small. The water holding capacity of meat
404 tends to be higher in the lighter carcasses. The trend for PL to increase with carcass weight at slaughter
405 may be related to the slower cooling rates in heavier carcasses. Relationships between carcass weight
406 or live weight and tenderness have sometimes been found in experimental studies on the effects of
407 prolonging the duration of fattening. In a study on Charolais heifers, Ellies-Oury et al. (2017) reported
408 a significant effect of slaughter weight on meat tenderness only with older animals, the lower values
409 associated with greater carcass weight, whereas no effect was found with younger animals. Similar
410 results were obtained by Sañudo et al. (2004), who reported that the meat of young bulls slaughtered at
411 550 kg live weight was more tender than that of young bulls slaughtered at 300 kg. In our study,
412 however, tenderness was the only quality trait unaffected by carcass weight.

413 **4.4. Effects of beef production system on carcass traits**

414 Our analyses revealed some unusual aspects as we tried to assess the effects of production system
415 on carcass and beef quality attributes within a single breed, a specific geographical area and relatively
416 homogeneous conditions. All the six production systems identified were characterised by on-farm
417 intensive fattening of animals, large use of cereal-based concentrate feeds and a lack of clear separation
418 between fattening and finishing periods.

419 In general, we observed a strong effect of production system on all carcass traits except carcass
420 weight. The weight at which animals are slaughtered is determined according to a combination of
421 animal characteristics, such as degree of maturity and body composition, and specific market
422 requirements. With conventional beef breeds and crossbred animals, diet composition and restricted
423 feeding may result in a large variation in fat deposition and, consequently, in the live weight at which
424 optimal carcass fatness is reached. This is not very evident in the case of double-muscled animals
425 (Schiavon & Bittante, 2014), which are not prone to becoming too fat. Weight at slaughter may,
426 therefore, be considered the main target, and the time needed to reach that target is the variable
427 reflecting the degree of efficiency of the production system. The traditional system with tied animals
428 seems to be highly disadvantaged compared with all the beef production systems using loose-housing,
429 as reflected by the lower daily carcass gain, which delays the age at which the animal is slaughtered,
430 and gives rise to a less favourable SEUROP classification and a smaller rib eye area. No significant
431 differences were found between the other beef production systems.

432 While our analyses were based on field data, most investigations into the effects of management
433 system on production traits have been carried out on experimental stations, often with a small number
434 of animals. A few practices have been compared, such as intensive vs extensive feeding systems
435 (Dannenberger et al., 2006; Guerrero et al., 2013; Daza et al., 2014) or, more specifically, the effects of
436 different diet compositions among conventional breeds (Johnson, Van Horn, West, & Harris, 1992;
437 Avilés et al. 2015). The results obtained were, therefore, then closely related to the design of the

438 experiment rather than answering a need to comply with market requirements. Conversely, a recent
439 study by Soulat et al. (2018) focused on the possibility to predict carcass quality of beef crossbred
440 heifers showing the importance of whole life rearing factors over carcass traits.

441 **4.5. Effects of beef production systems on meat quality traits**

442 In this study, the batch effect explained a large proportion of total variance in meat quality traits,
443 with the exception of pH. As this effect regards animals slaughtered on the same day, it encapsulates
444 the effects of pre-slaughter and slaughter conditions (Adzitey, 2011) and post-mortem handling of
445 carcasses (Warris, 2000). It also includes possible effects of calibration of the equipment used for the
446 physical analyses and of laboratory operators, which are important sources of variation in several meat
447 quality traits. In general, the effects of beef production system and of individual farm within production
448 system on meat quality traits were of a small magnitude. These findings agree with the principles
449 adopted by Meat Standards Australia (MSA) system (Bonny et al., 2018), which puts more focus on
450 slaughter conditions, carcass characteristics, ageing time and cooking techniques than on rearing
451 factors to deliver an eating quality guarantee to consumers.

452 In our study the effect of production systems was appreciable only for L*, reflecting the possible
453 influence of stall and feeding system on meat colour. Our results agree with Brugiapaglia & Destefanis
454 (2012), who found that the meat of tie-stalled Piemontese young bulls had higher L* and b* values than
455 those of animals fattened in pens. Indeed, the darker meat of animals reared in loose conditions could
456 be related with the muscle's greater oxidative capacity resulting from physical activity (Vestergaard,
457 Oksbjerg, & Henckel, 2000; Jurie, Ortigues-Marty, Picard, Micol & Hocquette, 2006). The anatomical
458 position of the muscle and its involvement in movement also play an important role in colour variation
459 (Dunne, O'Mara, Monahan, French, & Moloney, 2005).

460 Regarding feeding system, our study revealed that meat from animals on a TMR diet was associated
461 with lower L* values, resulting in a slightly darker colour, in agreement with the findings of Avilés et
462 al. (2015), who reported that meat from calves fed traditionally was paler than meat from TMR-fed

463 calves, although feeding system did not have a significant effect on the other colour traits. Jurie et al.
464 (2006) highlighted a combined effect of pasture and grass diet *vs.* maize silage-based diet on meat
465 colour, while other studies found no clear relationships between feeding system and meat colour
466 (French et al., 2001; Daza et al., 2014).

467 Apart from colour traits, the scientific literature provides no clear evidence of a relationship
468 between farm management and meat quality. Even when comparison have been made between
469 management systems with greater differences than those examined in this study, such as intensive *vs*
470 extensive fattening, results have often been inconsistent or conflicting. This tendency was also
471 observed in our study where no influence of production system on pH, shear force, PL and CL could be
472 detected. Consistent with our findings, studies by Daza et al. (2014), Cerdeño, Vieira, Serrano, Lavín,
473 & Mantecón (2006) and French et al. (2001) found no effect of feeding system on PL. Guerrero et al.
474 (2013) reported an effect of pre-finishing management of young bulls on PL but not on CL. More
475 recently, Gagaoua et al. (2018) highlighted an effect of carcass fatness over young bulls' meat
476 tenderness, juiciness and flavour. Moreover, they also reported that animals with shorter fattening
477 duration and lower body weight at the beginning of the fattening period were able to produce meat with
478 better eating quality. Soulat et al. (2018) showed that the prediction of meat quality traits obtained from
479 rearing factors were less accurate than those of carcass traits. Nevertheless age at slaughter, ease of
480 birth and genetic potential in muscular development could explain the eating quality of heifers' meat
481 appraised by a tasting panel.

482 **4.6. How carcass and meat quality traits will change in future**

483 As already mentioned in this study, the main change to the beef production systems in the case
484 study area has been the gradual replacement of the traditional system of tied animals with systems
485 using loose-housing. The results obtained here confirm that, aside from improvement in animal welfare
486 and production ethics which are key issues for the European consumers (Hocquette et al., 2018), this

487 trend would greatly improve the animal's production efficiency (daily carcass gain and conformation)
488 without having any undesired effect on meat quality, with the only exception of meat lightness. This
489 goes in the direction of a broader concept relative to a sustainable efficient livestock production, as
490 highlighted by Scollan et al. (2011) and by Hocquette et al. (2018) analysing the future research
491 priorities for animal production. Among the 5 beef systems using loose-housing, there were many
492 differences in terms of number of the manageable animals, capital investments, labour requirements,
493 feeds and welfare issues, with modern systems using TMR fed *ad libitum* being the more efficient.
494 However, the carcass and meat quality traits did not differ much between systems, so no major changes
495 in these traits should be expected in the future as a consequence of changes in farming systems.

496 Within beef production systems, however, there was large variability among individual farms in
497 carcass weight and daily carcass gain, and particularly for age at slaughter, but not for EUS. A great
498 variability among farms was highlighted also in other studies regarding economic and environmental
499 performances (Veysset, Lherm, & Bébin, 2010; Veysset, Lherm, & Bébin, 2011). This variability
500 should be studied in greater detail to understand which factors, not considered in the present study, may
501 be affecting carcass traits and how they could be exploited to improve production efficiency.

502 The small effect of beef production system and of individual farm within beef system makes it clear
503 that the variability in carcass conformation and meat quality traits depends mainly on individual animal
504 factors and that improvements to them can be made by taking action at the level of individual animals.
505 As the most important individual factor explaining meat quality was carcass weight class, it is
506 important to understand the extent to which this effect depends on growth rate potential, fat deposition
507 rate, length of fattening period and carcass yield. As only genetics can yield durable improvements in
508 carcass and meat quality, further knowledge of the genetic mechanisms underlying the variations in
509 these traits also needs to be acquired.

510 **5. Conclusions**

511 This study provides a detailed description of beef production systems using as a case study the
512 Piemontese breed, which exemplifies the main beef production systems classified by the European
513 Union. Six main types, according to specific management strategies were identified. Traditional
514 systems coexist alongside more advanced systems using modern technologies. Within the production
515 systems identified, there is still a considerable variation among farms. Carcass traits are strongly
516 affected by production system, with traditional management conditions having lower production
517 efficiency. However, production system exerts only a very small effect on meat quality, limited to
518 colour traits. It appears that meat quality may be conditioned by other factors related to individual
519 animals within farms, suggesting that future improvement should look, in particular, to genetics.

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713 **Table 1.** Profiles of beef production systems identified by hierarchical cluster analysis on the basis of
 714 the following binary variables: beef production system (Breeders&fatteners *vs* specialised fatteners),
 715 housing system (tie-stalls *vs* loose-housing), feed supply (restricted *vs ad libitum*) and feed distribution
 716 (TMR *vs* separate distribution of concentrates and forage).

Cluster	Sampled (n):		Incidence on farms (%)			
	Farms	Young bulls	Integrated cow-calf and fattening	Ad libitum feeding (ad lib)	Total Mixed Ration (TMR)	Loose housing system (pens)
All farms	115	1,327	50	66	30	77
Traditional systems ^a						
Tie-stalls	24	160	63	25	0	0
Pens	21	196	48	0	19	100
Breeders-fatteners, <i>ad lib</i> :						
TMR	14	218	100	100	100	100
No TMR	18	208	100	100	0	100
Fatteners, <i>ad lib</i> :						
TMR	16	200	0	100	100	88
No TMR	22	345	0	100	0	100

717 ^aAdopting restricted feeding.

718 **Table 2.** Descriptive statistics and effect of beef production system on farm size, yearly production and
 719 space allowance of animals.

	Farm size, ha	Slaughtered animals, n×ha ⁻¹	Slaughtered animals, n×yr ⁻¹	Space allowance, m ² ×head ⁻¹
General mean	39.2	2.55	82.3	4.66
Standard deviation	26.4	4.20	111.5	2.44
Traditional systems ^a				
Tie-stalls	27.4	1.77	46.0	2.00
Pens	32.1	1.92	63.9	5.20
Breeder-fatteners, <i>ad lib</i> :				
TMR ^b	51.5	1.41	59.6	6.20
No TMR ^b	44.0	0.83	34.8	6.01
Fatteners, <i>ad lib</i> :				
TMR ^b	58.7	3.76	163.7	4.62
No TMR ^b	33.7	5.43	137.0	5.00
Contrasts (estimate):				
Tie-stall <i>vs</i> loose-housing ¹	-13.0*	-0.62	-27.8	-3.60**
Restricted <i>vs</i> <i>ad lib</i> ²	-14.9*	-0.94	-34.9	-0.25
Breeders-fattener <i>vs</i> fatteners ³	1.5	-3.48**	-103.1**	1.30**
TMR ^b <i>vs</i> no TMR ^{b,4}	16.3**	-0.54	25.7	-0.10
Interaction ⁵	8.8	-1.12	0.9	-0.29
RMSE	24.6	3.97	103.3	2.00

720 ^aRestricted feeding

721 ^bTotal mixed ration

722 * $P < 0.05$.

723 ** $P < 0.01$.

724 ¹Traditional tie-stalls *vs* (Traditional tie-stalls + breeders-fatteners-noTMR + breeders-fatteners-TMR +
 725 fatteners-noTMR + fatteners-TMR)

726 ²Traditional pens *vs* (breeders-fatteners-noTMR + breeders-fatteners-TMR + fatteners-noTMR +
 727 fatteners-TMR)

728 ³(breeders-fatteners-noTMR + breeders-fatteners-TMR) *vs* (fatteners-noTMR + fatteners-TMR)

729 ⁴(breeders-fatteners-noTMR + fatteners-noTMR) *vs* (breeders-fatteners-TMR + fatteners-TMR)

730 ⁵(breeders-fatteners-TMR + fatteners-noTMR) *vs* (breeder-fatteners-noTMR + breeders-TMR)

731 **Table 3.** Descriptive statistics and effect of beef production system on subjective evaluation of animal
 732 facilities by technicians (1=poor, 2=average, 3=good).

	Building adequacy	Cleaness condition	Aeration efficiency	Water availability	Animal docility	Overall evaluation
General mean	2.11	2.16	2.04	2.73	2.78	2.29
Standard deviation	0.75	0.65	0.77	0.52	0.46	0.52
Traditional systems ^a						
Tie-stalls	1.38	1.79	1.42	2.54	2.62	1.81
Pens	2.14	1.95	2.10	2.52	2.71	2.20
Breeder-fatteners, <i>ad lib</i> :						
TMR ^b	2.43	2.29	2.43	3.00	2.93	2.56
No TMR ^b	2.06	2.33	2.22	2.72	2.89	2.35
Fatteners, <i>ad lib</i> :						
TMR ^b	2.73	2.47	2.47	2.93	2.87	2.69
No TMR ^b	2.29	2.33	2.00	2.81	2.76	2.39
Contrasts (<i>estimate</i>):						
Tie-stall <i>vs</i> loose-housing ¹	-0.85**	-0.45**	-0.77**	-0.22*	-0.20	-0.56**
Restricted <i>vs</i> <i>ad lib</i> ²	-0.23	-0.40**	-0.18	-0.34**	-0.15	-0.29**
Breeders-fattener <i>vs</i> fatteners ³	-0.27	-0.09	0.09	-0.01	0.09	-0.08
TMR ^b <i>vs</i> no TMR ^{b,4}	0.41**	0.04	0.34	0.20	0.07	0.26*
Interaction ⁵	0.04	0.09	0.13	-0.08	0.03	0.04
RMSE	0.62	0.61	0.70	0.50	0.45	0.44

733 ^aRestricted feeding

734 ^bTotal mixed ration

735 * P<0.05.

736 ** P<0.01

737 ¹Traditional tie-stalls *vs* (Traditional tie-stalls + breeders-fatteners-noTMR + breeders-fatteners-TMR +
 738 fatteners-noTMR + fatteners-TMR)

739 ²Traditional pens *vs* (breeders-fatteners-noTMR + breeders-fatteners-TMR + fatteners-noTMR +
 740 fatteners-TMR)

741 ³(breeders-fatteners-noTMR + breeders-fatteners-TMR) *vs* (fatteners-noTMR + fatteners-TMR)

742 ⁴(breeders-fatteners-noTMR + fatteners-noTMR) *vs* (breeders-fatteners-TMR + fatteners-TMR)

743 ⁵(breeders-fatteners-TMR + fatteners-noTMR) *vs* (breeder-fatteners-noTMR + breeders-TMR)

744 **Table 4.** Effect of beef production system on ingredient composition (% as fed) of concentrate mix and
 745 type of forage supply.

	Composition (% as fed) of concentrate mix given separately or mixed with hay in TMR:											Forages supplied
	Corn silage	Ear corn silage	Compound feed	Ground corn	Barley, wheat	Wheat bran ¹	Beet pulp	Soybean meal	Other proteins	Fats	M-V mix	
General mean	2.27	8.90	34.12	34.95	2.72	5.89	3.14	5.42	1.14	0.38	0.87	-
Standard deviation	8.37	21.07	37.22	23.95	5.53	7.57	5.18	6.63	3.31	0.92	1.39	-
Traditional systems ^a :												
Tie-stalls	1.75	2.29	48.58	30.71	5.28	6.58	0.42	3.25	0.92	-	0.25	<i>ad lib</i>
Pens	1.07	7.89	30.52	39.30	2.30	7.14	3.84	5.35	1.56	0.19	0.83	<i>ad lib</i>
Breeder-fatteners, <i>ad lib</i> :												
TMR ^b	1.79	32.50	10.51	33.53	1.22	4.53	4.39	9.90	-	0.56	1.08	12.6 ²
No TMR ^b	-	-	48.72	38.22	1.94	3.06	3.22	2.44	1.22	0.33	0.72	<i>ad lib</i>
Fatteners, <i>ad lib</i> :												
TMR ^b	8.94	18.99	12.19	34.00	1.16	7.45	4.27	7.59	1.78	1.14	1.43	12.2 ³
No TMR ^b	1.27	2.00	40.80	34.37	3.06	6.01	3.75	5.87	1.18	0.35	1.18	<i>ad lib</i>
Contrasts (<i>estimate</i>):												
Tie-stall vs loose-housing ¹	0.72	8.30	15.94*	-5.64	3.15*	1.40	-3.38	-2.64	-0.07	-0.36	-0.71*	-
Restricted vs <i>ad lib</i> ²	-1.93	-5.51	2.47	4.27	0.46	1.88	-0.07	-1.10	0.51	-0.41	-0.27	-
Breeders-fattener vs fatteners ³	-4.21*	5.76	3.12	1.69	-0.53	-2.94	-0.20	-0.56	-0.87	-0.30	-0.40	-
TMR ^b vs no TMR ^{b,c}	4.73*	24.7**	-33.41**	-2.53	-1.31	1.45	0.84	4.59**	-0.31	0.50*	0.30	-
Interaction ⁵	2.94	-7.76	4.80	2.17	-0.59	-0.01	-0.32	-2.87	0.91	0.28	-0.06	-
RMSE	8.09	18.58	34.84	24.29	5.45	7.59	5.08	6.34	3.34	0.87	1.37	-

746 ^aRestricted feeding

747 ^bTotal mixed ration

748 ¹Included other cereal byproducts and distillers and soybean hulls

749 ²% of total intake (on average 87.1% meadow hay and 12.9% barley or wheat straw)

750 ³% of total intake (on average 86.2% meadow hay and 13.8% barley or wheat straw)

751 * P<0.05.

752 ** P<0.01

753 ¹Traditional tie-stalls vs (Traditional tie-stalls + breeders-fatteners-noTMR + breeders-fatteners-TMR +
 754 fatteners-noTMR + fatteners-TMR)

755 ²Traditional pens vs (breeders-fatteners-noTMR + breeders-fatteners-TMR + fatteners-noTMR +
 756 fatteners-TMR)

757 ³(breeders-fatteners-noTMR + breeders-fatteners-TMR) vs (fatteners-noTMR + fatteners-TMR)

758 ⁴(breeders-fatteners-noTMR + fatteners-noTMR) vs (breeders-fatteners-TMR + fatteners-TMR)

759 ⁵(breeders-fatteners-TMR + fatteners-noTMR) vs (breeder-fatteners-noTMR + breeders-TMR)

760 **Table 5.** Descriptive statistics and effect of beef production system on nutrient composition of mix
 761 concentrates (% as fed). TMR^b net of forages amount.

	Crude protein	Crude fibre	Ether extract	Ashes
General mean	13.1	6.0	3.9	4.79
Standard deviation	1.8	1.6	1.0	1.4
Traditional systems ^a				
Tie-stalls	13.6	6.1	3.5	4.7
Pens	13.3	5.7	3.6	4.4
Breeder-fatteners, <i>ad lib</i>				
TMR ^b	12.8	5.9	3.6	4.1
No TMR ^b	13.6	6.1	4.2	6.0
Fatteners, <i>ad lib</i>				
TMR ^b	11.9	6.2	3.9	4.1
No TMR ^b	13.5	5.8	4.2	5.2
Contrasts (<i>estimate</i>)				
Tie-stall <i>vs</i> loose-housing ¹	0.3	0.2	-0.4	-0.3
Restricted <i>vs</i> <i>ad lib</i> ²	0.3	-0.3	-0.4	-0.5
Breeders-fattener <i>vs</i> fatteners ³	0.5	0.0	-0.1	0.4
TMR ^b <i>vs</i> no TMR ^{b,4}	-1.2**	0.0	-0.4	-1.5**
Interaction ⁵	-0.4	0.2	0.2	0.4
RMSE	1.7	1.7	1.0	1.3

762 ^aRestricted feeding

763 ^bTotal mixed ration

764 *P<0.05.

765 **P<0.01.

766 ¹Traditional tie-stalls *vs* (Traditional tie-stalls + breeders-fatteners-noTMR + breeders-fatteners-
 767 TMR + fatteners-noTMR + fatteners-TMR)

768 ²Traditional pens *vs* (breeders-fatteners-noTMR + breeders-fatteners-TMR + fatteners-noTMR +
 769 fatteners-TMR)

770 ³(breeders-fatteners-noTMR + breeders-fatteners-TMR) *vs* (fatteners-noTMR + fatteners-TMR)

771 ⁴(breeders-fatteners-noTMR + fatteners-noTMR) *vs* (breeders-fatteners-TMR + fatteners-TMR)

772 ⁵(breeders-fatteners-TMR + fatteners-noTMR) *vs* (breeder-fatteners-noTMR + breeders-TMR)

773 **Table 6.** Descriptive statistics, ANOVA, and effects of beef production system on age of
 774 Piemontese young bulls at slaughter and carcass traits.

	Age at slaughter d	Carcass weight kg	Carcass gain kg/d	SEUROP score ¹	Rib eye area cm ²
General mean	541	438	0.818	14.66	92.0
Standard deviation	63	44	0.107	1.54	14.3
ANOVA					
Slaughter batch ² (%)	7.1	8.9	4.7	6.8	17.6
Farm within system ² (%)	52.5	24.7	27.3	10.2	4.9
Birth season (<i>F-value</i>)	13.4**	1.6	4.5**	1.2	0.9
Parity of dam (<i>F-value</i>)	7.0**	2.7*	10.9**	0.8	0.4
Beef production system (<i>F-value</i>)	3.1*	0.6	4.8**	3.1*	2.3
Beef production system (<i>LS-means</i>)					
Traditional systems [#] :					
Tie-stalls	581	426	0.746	14.02	89.5
Pens	539	434	0.815	14.40	91.0
Breeder-fatteners, <i>ad lib</i> :					
TMR [§]	559	438	0.797	14.92	94.6
No TMR [§]	515	432	0.849	14.62	92.8
Fatteners, <i>ad lib</i> :					
TMR [§]	549	430	0.789	14.46	89.0
No TMR [§]	550	438	0.803	14.69	92.2
Contrasts (<i>estimate</i>):					
Tie-stall <i>vs</i> loose-housing ¹	40**	-10	-0.070**	-0.64**	-3.2*
Restricted <i>vs ad lib</i> ²	-4	2	0.005	-0.28	-1.2
Breeders-fattener <i>vs</i> fatteners ³	-13	1	0.027	0.20	3.1*
TMR [§] <i>vs</i> no TMR ^{§4}	21	-1	-0.033	0.04	-0.7
Interaction ⁵	-22	-7	0.019	-0.27	-2.5
RMSE	42.1	36.1	0.087	1.4	12.4

775 ¹Carcass conformation score (from S+=18 to P-=1)

776 ²Random factor variance expressed as % of total variance

777 * P<0.05.

778 ** P<0.01.

779 [#]Restricted feeding

780 [§]total mixed ration

781 ¹Traditional tie-stalls *vs* (Traditional tie-stalls + breeders-fatteners-noTMR + breeders-fatteners-
 782 TMR + fatteners-noTMR + fatteners-TMR)

783 ²Traditional pens *vs* (breeders-fatteners-noTMR + breeders-fatteners-TMR + fatteners-noTMR +
 784 fatteners-TMR)

785 ³(breeders-fatteners-noTMR + breeders-fatteners-TMR) *vs* (fatteners-noTMR + fatteners-TMR)

786 ⁴(breeders-fatteners-noTMR + fatteners-noTMR) *vs* (breeders-fatteners-TMR + fatteners-TMR)

787 ⁵(breeders-fatteners-TMR + fatteners-noTMR) *vs* (breeder-fatteners-noTMR + breeders-TMR)

788 **Table 7.** Descriptive statistics, ANOVA, and effects of beef production system and carcass weight
 789 on meat colour traits.

	L*	a*	b*	C*	h*
General mean	39.8	28.6	9.6	30.2	18.5
Standard deviation	3.5	1.7	1.7	2.1	2.0
ANOVA					
Slaughter batch ¹ (%)	19.3	24.2	22.4	23.6	21.1
Farm within system ¹ (%)	7.1	3.5	3.3	3.3	3.5
Birth season (<i>F-value</i>)	0.3	2.3	1.8	2.4	1.2
Parity of dam (<i>F-value</i>)	1.3	2.5	2.5	2.5	1.8
Beef production system (<i>F-value</i>)	3.1*	1.8	2.3	2.0	2.1
Carcass weight (<i>F-value</i>)	14.8**	31.3**	34.7**	33.6**	30.0**
Beef production system (<i>LS-means</i>)					
Traditional systems [#] :					
Tie-stalls	40.8	28.98	10.0	30.67	18.86
Pens	39.6	28.57	9.6	30.15	18.36
Breeder-fatteners, <i>ad lib</i> :					
TMR [§]	39.3	28.72	9.6	30.31	18.37
no TMR [§]	40.7	28.80	9.9	30.45	17.78
Fatteners, <i>ad lib</i> :					
TMR [§]	39.7	28.41	9.4	29.95	18.19
No TMR [§]	39.7	28.61	9.6	30.20	18.44
Contrasts (<i>estimate</i>):					
Tie-stall <i>vs</i> loose-housing ¹	0.9*	0.31	0.3	0.40	0.37
Restricted <i>vs ad lib</i> ²	-0.3	-0.06	-0.1	-0.08	-0.08
Breeders-fattener <i>vs</i> fatteners ³	0.4	0.25	0.3	0.31	0.26
TMR [§] <i>vs</i> no TMR ^{§4}	-0.8*	-0.14	-0.2	-0.19	-0.33
Interaction ⁵	0.6	-0.06	0.1	-0.05	0.08
Carcass weight (<i>LS-means</i>)					
<350 kg	38.8 ^a	27.7 ^a	8.6 ^a	29.0 ^a	17.1 ^a
351-400 kg	39.4 ^a	28.2 ^{a,b}	9.3 ^b	29.7 ^{a,b}	18.1 ^b
401-450 kg	39.4 ^a	28.5 ^b	9.5 ^b	30.1 ^b	18.4 ^b
451-500 kg	40.3 ^b	29.1 ^c	10.1 ^c	30.8 ^c	19.0 ^c
> 500 kg	41.9 ^c	29.9 ^d	11.0 ^d	31.9 ^d	20.0 ^d
RMSE	2.9	1.4	1.3	1.7	1.7

790 ^{a,b,c,d} = $P < 0.05$

791 ¹Random factor variance expressed as % of total variance.

792 * $P < 0.05$.

793 ** $P < 0.01$

794 [#]Restricted feeding

795 ⁹Total mixed ration

796 ¹Traditional tie-stalls *vs* (Traditional tie-stalls + breeders-fatteners-noTMR + breeders-fatteners-
797 TMR + fatteners-noTMR + fatteners-TMR)

798 ²Traditional pens *vs* (breeders-fatteners-noTMR + breeders-fatteners-TMR + fatteners-noTMR +
799 fatteners-TMR)

800 ³(breeders-fatteners-noTMR + breeders-fatteners-TMR) *vs* (fatteners-noTMR + fatteners-TMR)

801 ⁴(breeders-fatteners-noTMR + fatteners-noTMR) *vs* (breeders-fatteners-TMR + fatteners-TMR)

802 ⁵(breeders-fatteners-TMR + fatteners-noTMR) *vs* (breeder-fatteners-noTMR + breeders-TMR)

803 **Table 8.** Descriptive statistics, ANOVA, and effects of beef production system and carcass weight
 804 on meat quality traits.

	pH	Purge losses %	Cooking losses %	Shear force N
General mean	5.56	4.51	16.8	40.97
Standard deviation	0.06	1.20	3.4	10.36
ANOVA				
Slaughter batch ¹ (%)	63.1	13.6	43.1	41.8
Farm within system ¹ (%)	4.5	7.3	3.1	5.2
Birth season (<i>F-value</i>)	0.2	3.9*	0.5	3.4*
Parity of dam (<i>F-value</i>)	2.5	2.7*	0.7	0.7
Beef production system (<i>F-value</i>)	2.2	0.7	0.9	0.6
Carcass weight: (<i>F-value</i>)	3.9*	6.6**	4.5**	0.8
Beef production system (<i>LS-means</i>)				
Traditional systems [#] :				
Tie-stalls	5.54	4.24	16.28	39.47
Pens	5.55	4.23	16.54	39.30
Breeder-fatteners, <i>ad lib</i> :				
TMR [§]	5.56	4.24	16.42	40.68
No TMR [§]	5.55	4.47	16.08	40.21
Fatteners, <i>ad lib</i> :				
TMR [§]	5.55	4.44	16.37	40.00
No TMR [§]	5.56	4.38	15.85	41.17
Contrasts (<i>estimate</i>):				
Tie-stall <i>vs</i> loose-housing ¹	-0.010	-0.086	0.058	-0.87
Restricted <i>vs ad lib</i> ²	-0.006	-0.153	0.360	-1.22
Breeders-fattener <i>vs</i> fatteners ³	0.003	-0.059	0.144	-0.14
TMR [§] <i>vs</i> no TMR ^{§4}	0.004	-0.086	0.430	-0.35
Interaction ⁵	-0.009	0.146	0.089	-0.82
Carcass weight (<i>LS-means</i>)				
< 350 kg	5.55 ^{a,b}	3.67 ^a	15.2 ^a	38.52
351-400 kg	5.55 ^b	4.45 ^b	16.7 ^b	40.81
401-450 kg	5.55 ^b	4.38 ^b	16.8 ^b	40.56
451-500 kg	5.56 ^a	4.56 ^b	16.5 ^b	40.21
> 500 kg	5.55 ^{a,b}	4.62 ^b	16.1 ^{a,b}	40.59
RMSE	0.03	1.06	2.5	7.68

805 ^{a,b,c,d}=*P*<0.05

806

807 ¹Random factor variance expressed as % of total variance.

808 *P<0.05.

809 **P<0.01

810 #Restricted feeding

811 ^gTotal mixed ration

812 ¹Traditional tie-stalls *vs* (Traditional tie-stalls + breeders-fatteners-noTMR + breeders-fatteners-
813 TMR + fatteners-noTMR + fatteners-TMR)

814 ²Traditional pens *vs* (breeders-fatteners-noTMR + breeders-fatteners-TMR + fatteners-noTMR +
815 fatteners-TMR)

816 ³(breeders-fatteners-noTMR + breeders-fatteners-TMR) *vs* (fatteners-noTMR + fatteners-TMR)

817 ⁴(breeders-fatteners-noTMR + fatteners-noTMR) *vs* (breeders-fatteners-TMR + fatteners-TMR)

818 ⁵(breeders-fatteners-TMR + fatteners-noTMR) *vs* (breeder-fatteners-noTMR + breeders-TMR).

819

820 **Highlights**

- 821 • EU defined fattening systems are characterised using a case study.
- 822 • Six beef production systems in the fattening of the Piemontese breed can be identified.
- 823 • Carcass traits of Piemontese young bulls are strongly affected by production system.
- 824 • Beef production system exerts little effect on meat quality, limited to lightness.