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Certain relationships between Animal Performance, Sensory Quality and Nutritional Quality can be generalized between various experiments on animal of similar types

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Abstract

In the beef sector, one of the major challenges is to early predict carcass and meat quality and to jointly satisfy the multiple expectations of the various stakeholders. Thus, the objective of this study was to determine if the relationships among carcass, nutritional and sensory qualities established previously by Ellies-Oury et al. (2016) might be generalized to different type of animals.

The *Longissimus thoracis* muscles of 32 young Charolais bulls were analyzed in terms of sensory and nutritional quality (lipid content and fatty acid composition). These parameters of interest were linked together and to animal performances by using a clustering of variables.

Longissimus thoracis sensory and nutritional qualities appear sometimes antagonistic. Indeed, some "positive" sensory descriptors (juiciness, overall appreciation, overall flavor and overall odor) are negatively related to PUFA proportions. PUFA proportions are positively associated with carcass weight but in the same time with rancid/fish flavors. Moreover, CLA and *trans* MUFA proportions are positively associated with the "negative" descriptors of greasy feel and residues. To finish, carcass weight and ADG are negatively associated with some "positive" sensory descriptors except tenderness.

It can be concluded from this work that these relationships, that were already established in previous works, are robust between experiments.

In order to highlight robust and generalizable relationships in different contexts, it is now appropriate to apply this method to a larger database containing different traits and various characteristics of breed, slaughter ages, animal types, fattening practices, ...

Keywords

clustering of variables, animal performances, meat quality traits, fatty acid composition, nutritional value, prediction.

1. Introduction

The beef industry is made up of a set of links from farmers to consumers, through processors. Each of these intermediaries has specific expectations that are not necessarily consistent with each other. Among them, most of farmers have mainly expectations in terms of animal performance. In addition to the type of animal and its age, the carcass payment scale in Europe is mainly based on 3 parameters: weight, fattening state and conformation. Apart from a few specifications for which sensory and/or nutritional properties are specific expectations, otherwise, in most cases, these parameters are not taken into account in the remuneration of breeders (Monteils et al., 2017).

In cattle farming, as in most livestock farming, animal feed is the first item of expenditure (50% to 60% on average). It is therefore in the interests of farmers to select and breed efficient animals, that is to say, animals that are able to convert efficiently distributed feed into sales products (Ellies-Oury et al., 2020). This can have consequences on the nutritional and/or sensory properties of the meat from their carcasses.

Meat stakeholders main concern is the market structure and consumers' demands. The quality of carcasses (in terms of weight, composition or yields for example) is thus an important parameter for the meat sector, insofar as it determines the payment of the farmer, the remuneration of the intermediate link and the assurance of an optimized meat quality (i.e. satisfying the sometimes antagonistic interests of the various stakeholders of the chain ; Dockès et al., 2011).

In general, Europeans claim they want to favour food products that are good for their health in the coming years (Ellies-Oury et al., 2019; Hocquette et al., 2018). Meats have a relatively homogenous nutritional composition, at least for proteins. However, their content in lipids (ranging from 1-2% to around 15%; (Li, 2017; Normand et al., 2005)) and in saturated fatty acids (some of them being assumed to be detrimental to human health; (McAfee et al., 2010)) are quite variable. These heterogeneous compositions are thus likely to disturb the consumer.

The price of meat is the most important purchase criterion for 78% of the French, ahead of taste quality (46%) (Centre d'études et de Prospective, 2014). Ellies-Oury et al. (2019) specify in a recent study that 88% of the respondents would be interested in a system that would ensure a guaranteed level of meat tenderness and meat sensory quality at the time of purchase. Furthermore, 95% of these people would be willing to pay more for a cut of meat if such a system is implemented. Prediction models have previously attempted to establish response laws of muscle properties as a function of animal performances at farm or husbandry factors (Conanec et al., 2019; Ellies-Oury et al., 2020; Ellies-Oury et al., 2019; Hocquette et al., 2017; Soulat et al., 2018, 2016). Other work has aimed to establish a model for predicting meat quality based on carcass properties (Ellies-Oury et al., 2020; Ellies-Oury et al., 2019; Gagaoua et al., 2018). However, in the light of these various studies, it appears that the response laws and prediction models cannot always been scaled up through experiments. Indeed, for example, concerning tenderness, Gagaoua et al. (2018) indicate that the best and interesting discriminators were fattening duration and dry matter intake, whereas, according to Soulat et al. (2018), meat traits were improved by the genetic of heifers' parents (*i.e.*, calving ease and early muscularity) and when heifers were slaughtered older. **The aim of this work was thus to determine whether the relations highlighted between the different parameters of interest to the beef sector (animal performance, sensory quantity and nutritional quality) could be validated between experiments.** To do this, the method developed by Ellies-Oury et al. (2016) was applied in a similar way to the data collected in the present experiment. Briefly, we used the *ClustOfVar* approach on data established on animals of different breeds from those studied by Ellies-Oury et al. (2016). Developed to arrange variables into homogeneous clusters, this method allows dimension reduction and variable selection (Chavent et al., 2011). Thus, this study should make it possible to show whether the equations proposed by Ellies-Oury et al. (2016) are robust and generalizable to different types of production. The ultimate objective of this work is, in the long term, to predict meat qualities and performances based on different animal husbandry practices, in order to manage these practices and, ultimately, to achieve quality and performance objectives in line with demand.

2. Material and Methods

Animal breeding and slaughtering procedures respected the French animal protection legislation, including licensing of experimenters. The French Veterinary Services controlled and approved the procedures at the slaughterhouse and at experimental facilities.

2.1 Animal's management and slaughtering

All the experimental procedures performed in this study were approved by the Animal Ethics Committee of INRA-CIRAD-IFREMER (APAFIS#1765-2015091516305 V3).

A total of 32 young Charolais bulls (313 ± 29.5 days old, mean live weight 482 ± 25.8 kg) were given individually for 6 months a basal diet consisting in 60% roughage (40% of corn silage and 20% of grass silage) and 40% of concentrate (Herbipole, INRAE, 2018). Daily feed intake and animal's body weight were recorded every 2 weeks. The average daily gain during growth (ADG during growth) was calculated from birth to weaning (estimated to 45 kg) but also during the growth and the finishing period. The ingested quantities were recorded every two weeks, allowing to estimate total and averaged ingested quantities of each component of the diet.

Animals were slaughtered in the experimental slaughterhouse of the INRAE Research Centre in which the slaughter rates are more constrained than in a commercial slaughterhouse. That's why animals were slaughtered in four times (at four different slaughter date) at the same body weight (736 ± 39.5 kg). After 24 hours of food deprivation, animals were slaughtered in the experimental abattoir of the INRAE Research Centre, under standard conditions and in compliance with French welfare regulations. The carcasses were not electrically stimulated. They were chilled at 2°C in drying chambers during 24 hours, then stored at 4°C. A pH meter equipped with a glass electrode allowed to verify the ultimate pH 24h *post-mortem.* The aim was to have a pH in the *Longissimus thoracis* located between 5.7 and 5.9 between the 6th and 7th rib.

2.2 Animal performances

Average daily gain during the finishing period (ADG during the finishing period), finishing feed conversion efficiency (ADG during the finishing period / dry matter) and finishing consumption index (dry matter / ADG during the finishing period) were calculated using feed consumption (expressed as dry matter or energy intake) during the finishing period and the live weight at the beginning of the finishing period. Live weight and slaughter age were recorded at the slaughterhouse. Carcass weight was then determined at slaughter. The removal and dissection of the sixth rib joint allowed to assess its muscle, fat and bone proportions. According to Robelin & Geay (1975) regression equations, the composition of the carcass (in content and in proportions) was estimated, by using 1) the sixth rib muscle, fat and bone proportions and 2) the carcass weight and measurement of the fatty deposits of the 5th quarter (Alberti et al., 2008). Carcass yield was also determined.

The amounts in vitamin A and E in plasma were determined by HPLC-UV spectrophotometry adapted to bovine plasma (Scislowski et al., 2005).

Total antioxidant status (SAO) in plasma was measured by a method based on the absorbance of the ABTS°+ cation [2,2'-azinobis-(3-ethylbenzothiazoline-6-sulfonic acid)] previously described by (Gobert et al., 2009).

Plasma Malondialdehyde (MDA) was determined by HPLC fluorescence as described earlier by (Agarwal and Chase, 2002).

These parameters, evaluated on the blood of the animals, were considered to be relevant to animal performance, in particular because of the correlation that exists between efficiency and the antioxidant status of the animal as reported by Chauhan et al. (2016) in lambs and more generally because dietary antioxidants intake are known to affect growth (Catoni et al., 2008) Thus, animal performances were characterized by 26 variables (Table 1). Means of each of the 26 variables studied in this experiment are given in Supplementary Data.

2.3 Muscle sampling

Samples (around 700 g) of the *Longissimus thoracis* (LT) muscle from the 10th thoracic rib were collected 1-day *post mortem*. The muscle samples were conditioned and stored differently according to the further analyses.

Samples for sensory evaluation (around 500 g) were cut into steaks, vacuum packed and kept at 4°C for ageing (14 days). Each sample was then frozen and stored at -20°C awaiting sensory evaluation. A part of the remaining samples (50 g) was frozen in liquid nitrogen and kept at -80°C until analyses to determine enzyme activities, protein extraction and myosin heavy chain (MyHC) quantification. Another part of the samples (150g) was cut into pieces (around 0.5 cm cross-section), ground into fine and homogeneous powder in liquid nitrogen with a mixer mill (Retch MM 301, Hann Germany) and stored at -80°C until analyses for collagen determination, fatty acid composition and intramuscular fat content. Samples for one similar analysis were taken at the same anatomical position from one animal to another.

2.4. Muscular properties and sensory analysis

Total, insoluble and soluble collagen, cross-links (CLs) and proteoglycans (PG) of LT muscles were measured according to procedure previously described by Dubost et al. (2013a).

Myofibrillar proteins from the LT muscles were extracted on ice as previously described by Picard et al. (1994). The proteins were separated by SDS-PAGE electrophoresis according to Picard et al. (2011). The proportions of the various myosin heavy chains (MyHC) were quantified using densitometry with ImageQuant Software 5500 (Amersham Biosciences/GE Healthcare). MyHC-IIb percentages were totalled with those of MyHC-IIx.

Sensory analyses were done at INRAE "Le Magneraud" station. After 14 days of ageing, each sample was thawed at 4°C over 24 hours. The meat samples were cut into 1.5 thick steaks and cooked under domestic grills until the temperature measured with a temperature probe reached 55°C (typical in France). Steaks were grilled between 2 aluminum sheets, until the end-point temperature previously indicated in the geometric center of the steak was reached. After grilling, each steak was cut into portions that were immediately presented to 12 panellists trained in beef meat sensory analysis. Each sample was rated between 0 to 10 on an unstructured scale for the following attributes: tenderness, juiciness, overall appreciation, overall odor, overall flavor, rancid flavor, rancid odor, blood flavor, blood odor, fish flavor, fatty flavor, greasy feel, residues. The score 0 represented a very low rating of the descriptor (extremely tough, very dry, ...) as opposed to the score 10 which corresponds to a very high rating (extremely tender, extremely juicy, ...).

Six sensory session were organized. At each of these sessions, the 12 panelists evaluated 5 or 6 samples randomly selected. Each sample was assessed by each panelist.

The expert panelists were trained in accordance with the ISO standards ISO/TC as described by Gagaoua et al. (2016). The sessions were carried out in a sensory analysis room equipped with individual booths under artificial red light, in order to reduce the influence of the appearance of the samples. Each tasting booth was equipped with computer terminal linked to a fileserver running a sensory software (Fizz, version 2.20h; Biosystemes, Couternon, France) that facilitated the direct entry of assessor ratings. The variables composing sensory quality are reported in the table 2. Means of each of these variables studied in this experiment are given in Supplementary Data.

2.5. Fatty acids composition

Total lipids of LT muscle were extracted according to Folch et al. (1957) and quantified by gravimetry. The FAs were extracted from total lipids and then converted into methyl esters by transmethylation using borontrifluoride-methanol (14% solution) according the method of (Bauchart et al., 2005). Fatty acid methyl ester analysis was performed by GLC using a Peri 2100 chromatography system (Perichrom, Saulx-les-Chartreux, France) fitted with a CP-Sil 88 glass capillary column (Varian, Palo Alto, CA; length 100 m, dia. 0.25 mm) as previously described by Gruffat et al. (2020). The carrier gas was H_2, and the oven and flame ionization detector temperatures were as follows: oven temperature was programmed for 70°C for 30 s, 70 to 175°C at a rate of 20°C/min, 175°C for 25 min, then 175 to 215°C at a rate of 10°C/min, and finally 215°C for 41 min; injector and detector temperatures were 235 and 250°C, respectively. Total FAs were quantified using 19:0 as an internal standard. Their identification and the calculation of the response coefficients were done using a C4-C24 quantitative mix (Supelco, Bellafonte, PA).
The variables composing nutritional quality are reported in the table 3. Means of each of these variables studied in this experiment are given in Supplementary Data.

2.6. Statistical analysis

As previously indicated, in order to determine whether the associations observed between the different Parameters of Interest (PI: animal performance, sensory quantity and nutritional quality) can be scaled up through experiments, we applied the *ClustOfVar* (clustering of variables; (Chavent et al., 2011)) approach to the data collected in the present experiment for LT muscle (as this muscle was used in (Ellies-Oury et al., 2016) previous work).

Briefly, the proposed statistical methodology splits into 3 steps.

First, for each of the three PI, a hierarchical clustering of variables was applied to assess the links between the variables (within each PI) [step 1, figure 1]. The production of a tree structure within the variables allows to highlight hierarchical links between variables and to detect an ideal number of classes within the population (by defining a cut-off level). Clusters, grouping together the associated variables, were thus created. For each PI and each cluster, an Intermediate Score (IS) was calculated [step 1], the numerical IS summarizes all the numerical or categorical variables within the cluster.

More precisely, in the *ClustOfVar* method, the IS of a cluster is defined as the first principal component obtained from the *PCAmix* (principal component analysis for mixed data) method applied on the variables within the considered cluster. The underlying homogeneity criterion of a cluster is defined as the sum of correlation ratios (for categorical variables) and squared Pearson correlations (for numerical variables) to the synthetic numerical variable (the IS in the proposed statistical methodology), summarizing "as good as possible" all the variables in the cluster. Thus, a cluster of variables is defined as homogeneous when all the variables in the cluster are strongly linked to the corresponding numerical synthetic variable (the IS). Note that, more generally, the numerical synthetic variables of the clusters can also be used for dimension reduction or for recoding purpose. The IS scores reflect all the information contained in the obtained clusters as long as each cluster is homogeneous. To determine the suitable number of clusters for a given set of variables, a bootstrap approach has been also developed to evaluate the stability of the partitions of variables and then provide the best partition (Chavent et al., 2011). In the following, to interpret the IS, only the variables within the cluster having a squared correlation with the IS greater than 0.50 were used. Note that the variables selected may be positively or negatively correlated with the IS.

Then, a second *ClustOfVar* analysis was done on all the previously created IS, allowing to build Global Indexes (GI) that were characterized by the IS's that are the best correlated to these GI (square correlation greater than 0.50) [step 2, figure 1].

Finally, in step 3 [step 2, figure 1], these GI were lastly compared between the two experiments in order to highlight robust relationships. That for, variable associations within each GI were compared. Stable pairings from one experiment to another (constituting equivalent clusters) could thus be identified. Conversely, it was also possible to highlight the variables for which the associations were unstable, i.e. the variables that changed cluster between the two experiments.

3. RESULTS and DISCUSSION

3.1. Determination of linked variables in the present experiment

The first result is that it was possible to constitute clusters of variables and thus build Intermediate Scores (IS). In the first step, 5 Intermediate Scores [denoted AP1* to AP5*] were retained concerning Animal Performances (figure 2) and respectively 4 and 5 IS concerning Sensorial [SQ1* to SQ4*] (figure 3) and Nutritional Quality [NQ1* to NQ5*] (figure 4). The increase of each of these IS led to either an increase or a decrease of the variables that compose the cluster, as indicated in table 4.

The clusters associated variables known to be correlated, especially because the number of clusters for each PI is relatively high compared to the total number of variables per PI: 5 vs. 26 for Animal Performances, 4 vs. 20 for Sensory Quality and 5 vs. 57 for Nutritional Quality. As for Ellies-Oury et al (2016), the synthetic indexes highlighted reflect widely accepted relationships such as:

- the positive link between food efficiency and ADG,
- the positive link between the different sensory parameters,
- the negative association between PUFA's proportions and the proportions of SFA and MUFA,

In the second step, it was possible to build Global Indexes (GI) by making clusters within Intermediate Scores. Four GI were highlighted [GI1* to GI4*] (table 5; figure 5). With the exception of GI4*, which associated only ISs related to animal performance [AP2*, AP3* and AP5*], all other GIs associated ISs related to different PI:

<u>- GI1* associated positively NQ3*, SQ1* and SQ4*.</u> Thus, in this GI, the proportions of CLA and *trans* MUFA were positively associated with the sensorial descriptors of fatty flavor, rancid flavor, greasy feel and residues, but also with MyHCIIa isoforms and collagen content (total, insoluble and CLs contents). All these parameters were negatively linked to tenderness.

<u>- GI2* associated positively AP1* and negatively NQ1*, NQ2*, NQ4* and SQ3*.</u> The SQ2* Intermediate Score was also negatively associated in this GI, but as the square correlation was lower than 0.50, this IS was removed for the GI2* interpretation. In this GI, the proportions

of PUFA were positively associated with live and carcass weights but also with rancid and fish flavors. All these variables were negatively linked to the amounts of lipids, the amounts and proportions of SFA and MUFA, but also to the positive descriptors of juiciness, overall flavor, overall odor and overall appreciation.

- GI3* associates positively AP4* and NQ5*. According to the interrelations identified in this GI, the amounts of PUFA were positively associated with slaughter age and ADG between birth and weaning.

To finish with, the GI4* associated ingested quantities, feed efficiency, carcass yield and muscle development, finishing growth rate and MDA content.

As noted earlier, the *ClustOfVar* method allows to group together variables that share similar information and that are thus highly correlated to each other. The advantage of this method is that, in the same analysis, different types of variables (contents, proportions, ratios, ...) can be grouped together, without any problem of collinearity. This specificity of the clustering of variables is clearly useful in our case, in that some of the different variables used are in part redundant with each other. On the other hand, in the method used here, two successive clustering of variables were carried out (steps 1 and 2) in order to compare our results with those established by Ellies-Oury et al. (2016). This succession of clustering is at the origin of a loss of information that is likely to limit the identification of relationships between the studied variables all the more as, as previously indicated, only the variables having a square correlation with the IS greater than 0.50 were used.

The variable clustering approach aims to maximize a homogeneity criterion among the highly correlated variables. However, from one experiment to another one, the available variables might be different and the homogeneity criterion might thus be different.

To finish with, what might also be underlined, the stability of partitions of variables was evaluated with bootstrap approach (Chavent et al., 2011). However, other methods might have been developed to determine the suitable number of clusters of variables, and might have conducted to a number of clusters different, and thus to different associations between variables. Nevertheless, the evaluation of the associated variables under other conditions of determination of the number of clusters makes it possible to highlight that the general tendencies remain unchanged whatever the number of clusters finally formed.

In the light of the associations of variables found in this paper, it can be shown that the main conclusions previously established by Ellies-Oury et al. (2016) on the LT muscle of Angus, Blondes d'Aquitaine and Limousin bulls were also true in this new experiment on the same muscle collected on Charolais bulls.

For example, we established that juiciness and the descriptors of overall appreciation, overall flavor and overall odor were positively related to meat lipid content but negatively related to the proportions of PUFA and EPA. Moreover, it appears that the positive sensory descriptors of juiciness as well as the overall odor, flavor and appreciation descriptors were negatively associated to carcass weight and ADG during growth. ~~It can be hypothesized that this negative association is related to lower fat development of animals with a high ADG during growth, as already established by Ellies-Oury et al. (2016). Indeed, during growth, most of nutrients are used for muscle development instead of fat development and thus, intramuscular fat (IMF) is deposited at a lower rate than muscle proteins. On the contrary, IMF is deposited at a greater rate than muscle proteins during finishing period, since less nutrients are used for muscle growth (Pethick et al., 2004).~~

Positive sensory descriptors of juiciness, overall appreciation, overall flavor and overall odor were also negatively associated with nutritional value of meat. As described above, increasing lipid content in meat led in most publications to an increase in sensorial descriptors of tenderness, juiciness, flavor and overall acceptability scores in trained jury but also in consumer sensory panels (Garmyn et al., 2011; Hocquette et al., 2010; Jeremiah et al., 2003; Lorenzen et al., 2003; May et al., 1992; Mottram, 1998; Neely et al., 1998; O'Quinn et al., 2012; Savell et al., 1987; Smith et al., 1985). However, even if fat and fatty acids contribute to a large extent to meat sensory quality, they also contribute to the nutritional value of meat (Wood et al., 2008; Scollan et al., 2001, 2014; Wyness et al., 2011). Indeed, for human, the relationships between dietary fat, irrespective of the food source, with the incidence of various lifestyle diseases including cardiovascular diseases is well established and several health agencies have proposed specific guidelines. Some fatty acids are also known to affect human health in several ways, especially some SFAs, such as C16:0, that is known for their harmful properties on human health (Muchenje et al., 2009). In the case of beef, the fatty acids present in the adipocytes being mostly SFAs and MUFAs (Wood et al., 2008), fatter animals have higher SFA proportions in their muscles and, thus, deleterious fatty acids.

However, juiciness, flavor/odor and overall appreciations are positively related to amounts and proportions of C18:1, confirming by the same way, that the fatter the animals are, the higher the proportion of SFA and MUFA (and therefore of C18:1 which is the major fatty acid in MUFA) in the meat, the juicier the meat. These results confirm the conclusions of various studies (Dryden and Maechello, 1970; Garmyn et al., 2011; Melton et al., 1982; Westerling and Hedrick, 1979), that establish a positive correlation between beef palatability and C18:1. Moreover, this FA is known to be a "neutral" FA without any deleterious or beneficial impact on human health (Pereira and Vicente, 2013).

~~In addition, as previously indicated by Ellies-Oury et al. (2016), juiciness and the descriptors of overall appreciation, overall flavor and overall odor were positively related to meat lipid content but negatively related to the proportions of PUFA and EPA. This result is logical since, as explained above, the increase in lipids in meat leads to an increase in the proportions of SFA and MUFA and thus a decrease in the proportion of PUFA. PUFAs are widely recognized for their beneficial properties for human health, including EPA and DHA which can profoundly influence human health (Vahmani et al., 2015). Thus, once again, juiciness and the descriptors of overall appreciation, overall flavor and overall odor are negatively correlated with the health value of meat.~~ Surprisingly, the tenderness is negatively related to the proportions of CLA and CLA precursors. These FA are known to reduce body fat, cardiovascular diseases and cancer, and to modulate immune and inflammatory responses (Dilzer and Park, 2012; Whigham et al., 2000). This negative relationship is surprising since CLAs are mainly stored in triglycerides (that are storage lipids that increase with body fat). According to the literature, tenderness might also be negatively correlated to PUFA proportions, whereas its correlation with MUFA appears positive (Garmyn et al., 2011). In conclusion, it seems complicated to jointly obtain a meat with optimized sensory and nutritional properties. There is a need to understand the relationship between palatability, fatty acid composition and fat content, in order to ensure subsequently that tenderness, flavor, and juiciness are not compromised when selecting cattle with enhanced nutritional composition.

In the present work, n-3 and n-6 PUFA proportions were positively linked (and negatively linked to n-3 and n-6 PUFA amounts, these amounts being positively linked together). These conclusions are contrary to those of the literature as in some studies, increasing n-3 PUFA proportions matched with decreasing n-6 PUFA proportions, showing competition between these fatty acid families for the same set of elongation and desaturation enzymes (Lorenz et al., 2002;

Nuernberg et al., 2005). ~~Working on various bovine breeds, (Ellies-Oury et al., 2016) indicated that increasing n-3 PUFA proportions leads to an increase of n-6 PUFA proportions (n-3 PUFA amounts are also positively correlated with n-6 PUFA amounts), but this correlation was found to be breed dependent. In fact, in the literature, most studies compared diets rich in n-3 PUFA to diets rich in n-6 PUFA. It is then normal that an increase in one family of fatty acids is associated with a decrease in the other. In the present experiment, the animals were all fed the same diet (40% of corn silage, 20% of grass silage and 40% of concentrates) which provided both n-6 (corn and concentrates) and n-3 (grass silage) PUFA. Thus, the present results might stem from an animal diet impact, as it is widely accepted that cattle feed (enriched or not with certain PUFAs and in particular n-3 PUFA) might have a significant impact on the FA composition of the meat.~~

~~If (Ellies-Oury et al., 2016) has previously revealed a positive relation between collagen content and lipid content of beef, a link might here be established between collagen and cross link contents and fat-linked sensory descriptors such as fat flavor and greasy feel. All of these variables are also positively associated with the proportions of CLA and CLA precursors.~~

~~Collagen composition (total and insoluble collagen, CLs) was positively associated with residues and negatively with tenderness. This conclusion, which is the opposite of that of (Ellies-Oury et al., 2016), is however consistent with the results previously established in the literature, which associated the increase in collagen content with an increase in meat hardness (Destefanis et al., 2000; Dransfield et al., 2003; Dubost et al., 2013b; Lepetit, 2007; McCormick, 1999; Nishimura et al., 2009; Renand et al., 2001; Rhee et al., 2004; Torrescano et al., 2003).~~

No relationship was found between the proportions of the different myosin isoforms and the sensory quality of the meat, contrary to the results of the literature (Chriki et al., 2013; Crouse et al., 1991; Ellies-Oury et al., 2016; Jurie et al., 2007; Maltin et al., 1998; Therkildsen et al., 2002; Zamora et al., 1996), who established a positive association between oxidative metabolism and sensory quality. Nevertheless, the relationship appears controversial as other authors, such as (Picard et al., 2014), that have found a negative correlation between these same variables, depending on the muscle type and/or the breed of the animals. Thus, even though several studies reviewed by Guillemin et al. (2009) have previously considered that fiber metabolic and enzyme activities are notably implicated in meat quality traits and especially in tenderness, no significant interrelation are observed in the present work.

To finish, we logically establish that carcass butcher value (carcass yield and muscle development in the carcass) is associated with lower carcass fatness but positively with peroxidation intensity. As indicated above, the leaner the meat, the more PUFA proportions it contains. However, it is well known that the PUFAs present in beef are sensitive to oxidation especially as the level of antioxidants such as vitamins E and A is low (Durand et al., 2005). Thus, it is not surprising that carcass butcher value is positively associated with MDA levels, that is an index of peroxidation intensity and negatively associated with the total antioxidant status and vitamin A and E levels of meat, that are indicators of the protection level of PUFA against peroxidation (Durand et al., 2005). It would therefore be relevant to introduce antioxidants in the diet of animals with a high carcass butcher value, in order to maintain the nutritional value of their meat.

4. CONCLUSION

The objective of this work was to determine whether the relations highlighted between the different parameters of interest to the industry (animal performance, sensory quantity and nutritional quality) could be validated between experiments. In the present work, we used the *ClustOfVar* package to validate, with data from a new experiment, the relationships previously highlighted in the literature (Ellies-Oury et al., 2016). In the light of these associations of variables, it can be shown that the main conclusions previously established on the LT muscles (of Angus, Blonde d'Aquitaine and Limousine cattle), were also found in this new experiment on the same muscle but on a different breed (Charolais). Indeed, the generalization of the equations established between the Parameters of Interest can help to determine the compromises that it will be necessary to make in order to meet the expectations of the different links of the sector. It will thus be possible to propose "realistic" specifications adapted to the different breeders / operators / consumers. However, the generalizations have only been shown to apply for the *Longissimus thoracis* from young bulls finished under feedlot conditions and slaughtered when they achieved a set weight.

In order to widely generalize the established relationships, it is now appropriate to apply this method to a database containing different experiments with various characteristics. It will thus be possible to highlight robust and generalizable relationships in different contexts (different breeds, types of animals, ...).

This method was carried out until now on the LT muscle, which is commonly considered as the reference muscle. However, in the light of various studies, it appears that the response laws and prediction models cannot always been scaled up through muscles within the same experiment. Thus, now that it has been proven that the relationships between the Parameters of Interest (animal performance, sensory quality, nutritional quality) can be transposed from one experiment to another on the same muscle, it is necessary to determine whether the proximities established between the three Parameters of Interest could be extrapolated from one muscle to another within the same carcass. It would then be possible to predict the properties of all the muscles of the carcass by knowing the properties of one of them. ~~Such predictive equations of the nutritional and sensory properties of the various muscles of the carcass would be of real interest to the~~

~~industry. Thus, in the long run, it should be possible to integrate these equations into a mathematical model for the management of animals in order to obtain meats whose properties will perfectly meet the expectations of the different markets / market niches.~~

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References

Agarwal, R., Chase, S.D., 2002. Rapid, fluorimetric–liquid chromatographic determination of malondialdehyde in biological samples. J. Chromatogr. B 775, 121–126.

Bauchart, D., Gladine, C., Gruffat, D., Leloutre, L., Durand, D., 2005. Effects of diets supplemented with oil seeds and vitamin E on specific fatty acids of rectus abdominis muscle in Charolais fattening bulls. Indic. Milk Beef Qual. 112, 431–436.

Catoni, C., Peters, A., Schaefer, H.M., 2008. Life history trade-offs are influenced by the diversity, availability and interactions of dietary antioxidants. Anim. Behav. 76, 1107–1119.

Centre d'études et de Prospective, E., 2014. Consommations et pratiques alimentaires durables: analyse de données nationales issues d'enquêtes d'opinion. Analyse.

Chauhan, S.S., Ponnampalam, E.N., Celi, P., Hopkins, D.L., Leury, B.J., Dunshea, F.R., 2016. High dietary vitamin E and selenium improves feed intake and weight gain of finisher lambs and maintains redox homeostasis under hot conditions. Small Rumin. Res. 137, 17–23.

Chavent, M., Kuentz, V., Liquet, B., Saracco, L., 2011. ClustOfVar: an R package for the clustering of variables. ArXiv Prepr. ArXiv11120295 50(13).

Chriki, S., Renand, G., Picard, B., Micol, D., Journaux, L., Hocquette, J.F., 2013. Meta-analysis of the relationships between beef tenderness and muscle characteristics. Livest. Sci. 155, 424–434. https://doi.org/10.1016/j.livsci.2013.04.009

Conanec, A., Picard, B., Durand, D., Cantalapiedra-Hijar, G., Chavent, M., Denoyelle, C., Gruffat, D., Normand, J., Saracco, J., Ellies-Oury, M.-P., 2019. New Approach Studying Interactions Regarding Trade-Off between Beef Performances and Meat Qualities. Foods 8, 197.

Crouse, J.D., Koohmaraie, M., Seideman, S.D., 1991. The relationship of muscle fibre size to tenderness of beef. Meat Sci. 30, 295–302. https://doi.org/10.1016/0309-1740(91)90039-S

Destefanis, G., Barge, M.T., Brugiapaglia, A., Tassone, S., 2000. The use of principal component analysis (PCA) to characterize beef. Meat Sci. 56, 255–259. https://doi.org/10.1016/S0309-1740(00)00050-4

Dilzer, A., Park, Y., 2012. Implication of conjugated linoleic acid (CLA) in human health. Crit. Rev. Food Sci. Nutr. 52, 488–513.

Dockès, A.-C., Magdelaine, P., Daridan, D., Guillaumin, A., Rémondet, M., Selmi, A., Gilbert, H., Mignon-Grasteau, S., Phocas, F., 2011. Attentes en matière d'élevage des acteurs de la sélection animale, des filières de l'agroalimentaire et des associations. Prod. Anim. 24, 285.

Dransfield, E., Martin, J.F., Bauchart, D., Abouelkaram, S., Lepetit, J., Culioli, J., Jurie, C., Picard, B., 2003. Meat quality and composition of three muscles from French cull cows and young bulls. Anim. Sci. 76, 387–399.

Dryden, F.D., Maechello, J.A., 1970. Influence of total lipid and fatty acid composition upon the palatability of three bovine muscles. J. Anim. Sci. 31, 36–41.

Dubost, A., Micol, D., Picard, B., Lethias, C., Andueza, D., Bauchart, D., Listrat, A., 2013a. Structural and biochemical characteristics of bovine intramuscular connective tissue and beef quality. Meat Sci. 95, 555–561. https://doi.org/10.1016/j.meatsci.2013.05.040

Dubost, A., Micol, D., Picard, B., Lethias, C., Andueza, D., Bauchart, D., Listrat, A., 2013b. Structural and biochemical characteristics of bovine intramuscular connective tissue and beef quality. Meat Sci. 95, 555–561.

Durand, D., Scislowski, V., Gruffat, D., Chilliard, Y., Bauchart, D., 2005. High-fat rations and lipid peroxidation in ruminants: consequences on the health of animals and quality of their products. Indic. Milk Beef Qual. 112, 137–150.

Ellies-Oury, M.-P., Cantalapiedra-Hijar, G., Durand, D., Gruffat, D., Listrat, A., Micol, D., Ortigues-Marty, I., Hocquette, J.-F., Chavent, M., Saracco, J., others, 2016. An innovative approach combining Animal Performances, nutritional value and sensory quality of meat. Meat Sci. 122, 163–172.

Ellies-Oury, M.P., Chavent, M., Conanec, A., Bonnet, M., Picard, B., Saracco, J., 2019. Statistical model choice including variable selection based on variable importance: A relevant way for biomarkers selection to predict meat tenderness. Sci. Rep. 9, 10014.

Ellies-Oury, M.-P., Hocquette, J.-F., Chriki, S., Conanec, A., Farmer, L., Chavent, M., Saracco, J., 2020. Various Statistical Approaches to Assess and Predict Carcass and Meat Quality Traits. Foods 9, 525.

Ellies-Oury, M.-P., Lee, A., Jacob, H., Hocquette, J.-F., 2019. Meat consumption–what French consumers feel about the quality of beef? Ital. J. Anim. Sci. 18, 646–656.

Folch, J., Lees, M., Stanley, G., 1957. A simple method for total lipid extraction and purification. J Biol Chem 226, 18.

Gagaoua, M., Bonnet, M., Ellies-Oury, M.P., de Koning, L., Picard, B., 2018. Reverse phase protein arrays for the identification/validation of biomarkers of beef texture and their use for early classification of carcasses. Food Chem. 245–252. https://doi.org/10.1016/j.foodchem.2018.01.070

Gagaoua, M., Terlouw, C., Micol, D., Hocquette, J.-F., Moloney, A.P., Nuernberg, K., Bauchart, D., Boudjellal, A., Scollan, N., Richardson, R.I., 2016. Sensory quality of meat from eight different types of cattle in relation with their biochemical characteristics. J. Integr. Agric. 15, 1550–1563.

Garmyn, A.J., Hilton, G.G., Mateescu, R.G., Morgan, J.B., Reecy, J.M., Tait, R.G., Beitz, D.C., Duan, Q., Schoonmaker, J.P., Mayes, M.S., others, 2011. Estimation of relationships between mineral concentration and fatty acid composition of longissimus muscle and beef palatability traits. J. Anim. Sci. 89, 2849–2858. https://doi.org/10.2527/jas.2010-3497

Gobert, M., Martin, B., Ferlay, A., Chilliard, Y., Graulet, B., Pradel, P., Bauchart, D., Durand, D., 2009. Plant polyphenols associated with vitamin E can reduce plasma lipoperoxidation in dairy cows given n-3 polyunsaturated fatty acids. J. Dairy Sci. 92, 6095–6104.

Gruffat, D., Durand, D., Rivaroli, D., Do Prado, I.N., Prache, S., 2020. Comparison of muscle fatty acid composition and lipid stability in lambs stall-fed or pasture-fed alfalfa with or without sainfoin pellet supplementation. animal 14, 1093–1101.

Guillemin, N., Cassar-Malek, I., Hocquette, J.F., Jurie, C., Micol, D., Listrat, A., Leveziel, H., Renand, G., Picard, B., 2009. La maîtrise de la tendreté de la viande bovine: identification de marqueurs biologiques. Prod. Anim. 22, 331.

Hocquette, J.-F., Bonny, S., Polkinghorne, R., Farmer, L., Legrand, I., Allen, P., Wierzbicki, J., Gardner, G., Pethick, D., 2017. Update on a European beef eating quality model, in: Sustainable Beef Quality for Europe-II-A Workshop for Industry and Scientists. p. np.

Hocquette, J.-F., Ellies-Oury, M.-P., Lherm, M., Pineau, C., Deblitz, C., Farmer, L., 2018. Current situation and future prospects for beef production in Europe—A review. Asian-Australas. J. Anim. Sci. 31, 1017.

Hocquette, J.F., Gondret, F., Baéza, E., Médale, F., Jurie, C., Pethick, D.W., 2010. Intramuscular fat content in meat-producing animals: development, genetic and nutritional control, and identification of putative markers. Animal 4, 303–319. http://dx.doi.org/10.1017/S1751731109991091

Jeremiah, L.E., Dugan, M.E.R., Aalhus, J.L., Gibson, L.L., 2003. Assessment of the chemical and cooking properties of the major beef muscles and muscle groups. Meat Sci. 65, 985–992.

Jurie, C., Picard, B., Hocquette, J.-F., Dransfield, E., Micol, D., Listrat, A., 2007. Muscle and meat quality characteristics of Holstein and Salers cull cows. Meat Sci. 77, 459–466. https://doi.org/10.1016/j.meatsci.2007.04.014

Lepetit, J., 2007. A theoretical approach of the relationships between collagen content, collagen cross-links and meat tenderness. Meat Sci. 76, 147–159. https://doi.org/10.1016/j.meatsci.2006.10.027

Li, C., 2017. The role of beef in human nutrition and health. Dikeman E Ed. Saf. Qual. Prod. Beef 2, 329–38.

Lorenz, S., Buettner, A., Ender, K., Nürnberg, G., Papstein, H.-J., Schieberle, P., Nürnberg, K., 2002. Influence of keeping system on the fatty acid composition in the longissimus muscle of bulls and odorants formed after pressure-cooking. Eur. Food Res. Technol. 214, 112–118.

Lorenzen, C.L., Miller, R.K., Taylor, J.F., Neely, T.R., Tatum, J.D., Wise, J.W., Buyck, M.J., Reagan, J.O., Savell, J.W., 2003. Beef customer satisfaction: Trained sensory panel ratings and Warner-Bratzler shear force values. J. Anim. Sci. 81, 143–149.

Maltin, C.A., Sinclair, K.D., Warriss, P.D., Grant, C.M., Porter, A.D., Delday, M.I., Warkup, C.C., 1998. The effects of age at slaughter, genotype and finishing system on the biochemical properties, muscle fibre type characteristics and eating quality of bull beef from suckled calves. Anim. Sci. 66, 341–348.

May, S.G., Dolezal, H.G., Gill, D.R., Ray, F.K., Buchanan, D.S., 1992. Effect of days fed, carcass grade traits, and subcutaneous fat removal on postmortem muscle characteristics and beef palatability. J. Anim. Sci. 70, 444–453. https://doi.org//1992.702444x

McAfee, A.J., McSorley, E.M., Cuskelly, G.J., Moss, B.W., Wallace, J.M., Bonham, M.P., Fearon, A.M., 2010. Red meat consumption: An overview of the risks and benefits. Meat Sci. 84, 1–13.

McCormick, R.J., 1999. Extracellular modifications to muscle collagen: implications for meat quality. Poult. Sci. 78, 785–791.

Melton, S.L., Amiri, M., Davis, G.W., Backus, W.R., 1982. Flavor and chemical characteristics of ground beef from grass-, forage-grain-and grain-finished steers. J. Anim. Sci. 55, 77–87.

Monteils, V., Sibra, C., Ellies-Oury, M.-P., Botreau, R., De la Torre, A., Laurent, C., 2017. A set of indicators to better characterize beef carcasses at the slaughterhouse level in addition to the EUROP system. Livestock science 202, 44–51.

Mottram, D.S., 1998. Flavour formation in meat and meat products: a review. Food Chem. 62, 415–424. https://doi.org/10.1016/S0308-8146(98)00076-4

Muchenje, V., Dzama, K., Chimonyo, M., Strydom, P.E., Hugo, A., Raats, J.G., 2009. Some biochemical aspects pertaining to beef eating quality and consumer health: A review. Food Chem. 112, 279–289.

Neely, T.R., Lorenzen, C.L., Miller, R.K., Tatum, J.D., Wise, J.W., Taylor, J.F., Buyck, M.J., Reagan, J.O., Savell, J.W., 1998. Beef customer satisfaction: role of cut, USDA quality grade, and city on in-home consumer ratings. J. Anim. Sci. 76, 1027–1033.

Nishimura, T., Fang, S., Wakamatsu, J., Takahashi, K., 2009. Relationships between physical and structural properties of intramuscular connective tissue and toughness of raw pork. Anim. Sci. J. 80, 85–90. https://doi.org/10.1111/j.1740-0929.2008.00600.x

Normand, J., Bastien, D., Bauchart, D., Chaigneau, F., Chesneau, G., Doreau, M., Farrié, J.P., Joulié, A., Le Pichon, D., Peyronnet, C., others, 2005. Produire de la viande bovine enrichie en acides gras polyinsaturés oméga 3 à partir de graines de lin: quelles modalités d'apport du lin, quelles conséquences sur la qualité de la viande? Renc Rech Rumin. 12, 359–366.

Nuernberg, K., Dannenberger, D., Nuernberg, G., Ender, K., Voigt, J., Scollan, N.D., Wood, J.D., Nute, G.R., Richardson, R.I., 2005. Effect of a grass-based and a concentrate feeding system on meat quality characteristics and fatty acid composition of longissimus muscle in different cattle breeds. Livest. Prod. Sci. 94, 137–147.

O'Quinn, T.G., Brooks, J.C., Polkinghorne, R.J., Garmyn, A.J., Johnson, B.J., Starkey, J.D., Rathmann, R.J., Miller, M.F., 2012. Consumer assessment of beef strip loin steaks of varying fat levels. J. Anim. Sci. 90, 626–634. https://doi.org/10.2527/jas.2011-4282

Pereira, P.M. de C.C., Vicente, A.F. dos R.B., 2013. Meat nutritional composition and nutritive role in the human diet. Meat Sci. 93, 586–592.

~~Pethick, D.W., Harper, G.S., Oddy, V.H., 2004. Growth, development and nutritional manipulation of marbling in cattle: a review. Aust. J. Exp. Agric. 44, 705–715.~~

Picard, B., Barboiron, C., Chadeyron, D., Jurie, C., 2011. Protocol for high-resolution electrophoresis separation of myosin heavy chain isoforms in bovine skeletal muscle. Electrophoresis 32, 1804–1806. https://doi.org/10.1002/elps.201100118

Picard, B., Gagaoua, M., Micol, D., Cassar-Malek, I., Hocquette, J.-F., Terlouw, C.E., 2014. Inverse relationships between biomarkers and beef tenderness according to contractile and metabolic properties of the muscle. J. Agric. Food Chem. 62, 9808–9818. https://doi.org/10.1021/jf501528s

Picard, B., Leger, J., Robelin, J., 1994. Quantitative determination of type I myosin heavy chain in bovine muscle with anti myosin monoclonal antibodies. Meat Sci. 36, 333–343. https://doi.org/10.1016/0309-1740(94)90130-9

Robelin, J., Geay, Y., 1975. Estimation de la composition de la carcasse des taurillons a partir de la composition de la 6eme cote. Bull. Tech. Cent. Rech. Zootech. Veterinaires Theix.

Renand, G., Picard, B., Touraille, C., Berge, P., Lepetit, J., 2001. Relationships between muscle characteristics and meat quality traits of young Charolais bulls. Meat Sci. 59, 49–60.

Rhee, M.S., Wheeler, T.L., Shackelford, S.D., Koohmaraie, M., 2004. Variation in palatability and biochemical traits within and among eleven beef muscles. J. Anim. Sci. 82, 534–550.

Savell, J.W., Branson, R.E., Cross, H.R., Stiffler, D.M., Wise, J.W., Griffin, D.B., Smith, G.C., 1987. National consumer retail beef study: Palatability evaluations of beef loin steaks that differed in marbling. J. Food Sci. 52, 517–519.

Scislowski, V., Bauchart, D., Gruffat, D., Laplaud, P.M., Durand, D., 2005. Effects of dietary n-6 or n-3 polyunsaturated fatty acids protected or not against ruminal hydrogenation on plasma lipids and their susceptibility to peroxidation in fattening steers. J. Anim. Sci. 83, 2162–2174.

Scollan, N.D., Choi, N.-J., Kurt, E., Fisher, A.V., Enser, M., Wood, J.D., 2001. Manipulating the fatty acid composition of muscle and adipose tissue in beef cattle. Br. J. Nutr. 85, 115–124.

Scollan, N.D., Dannenberger, D., Nuernberg, K., Richardson, I., MacKintosh, S., Hocquette, J.-F., Moloney, A.P., 2014. Enhancing the nutritional and health value of beef lipids and their relationship with meat quality. Meat Sci., Advancing Beef Safety through Research and Innovation: Prosafebeef 97, 384–394. https://doi.org/10.1016/j.meatsci.2014.02.015

Smith, G.C., Carpenter, Z.L., Cross, H.R., Murphey, C.E., Abraham, H.C., Savell, J.W., Davis, G.W., Berry, B.W., Parrish, F.C., 1985. Relationship of USDA marbling groups to palatability of cooked beef. J. Food Qual. 7, 289–308.

Soulat, J., Picard, B., Léger, S., Ellies-Oury, M.-P., Monteils, V., 2018. Preliminary study to determinate the effect of the rearing managements applied during heifers' whole life on carcass and flank steak quality. Foods 7, 160.

Soulat, J., Picard, B., Léger, S., Monteils, V., 2016. Prediction of beef carcass and meat traits from rearing factors in young bulls and cull cows. J. Anim. Sci. 94, 1712–1726.

Therkildsen, M., Melchior Larsen, L., Bang, H.G., Vestergaard, M., 2002. Effect of growth rate on tenderness development and final tenderness of meat from Friesian calves. Animal 74, 253–264.

Torrescano, G., Sanchez-Escalante, A., Gimenez, B., Roncales, P., Beltrán, J.A., 2003. Shear values of raw samples of 14 bovine muscles and their relation to muscle collagen characteristics. Meat Sci. 64, 85–91.

Vahmani, P., Mapiye, C., Prieto, N., Rolland, D.C., McAllister, T.A., Aalhus, J.L., Dugan, M.E., 2015. The scope for manipulating the polyunsaturated fatty acid content of beef: a review. J. Anim. Sci. Biotechnol. 6, 29.

Westerling, D.B., Hedrick, H.B., 1979. Fatty acid composition of bovine lipids as influenced by diet, sex and anatomical location and relationship to sensory characteristics. J. Anim. Sci. 48, 1343–1348.

Whigham, L.D., Cook, M.E., Atkinson, R.L., 2000. Conjugated linoleic acid: implications for human health. Pharmacol. Res. 42, 503–510.

Wood, J.D., Enser, M., Fisher, A.V., Nute, G.R., Sheard, P.R., Richardson, R.I., Hughes, S.I., Whittington, F.M., 2008. Fat deposition, fatty acid composition and meat quality: A review. Meat Sci. 78, 343–358. https://doi.org/10.1016/j.meatsci.2007.07.019

Wyness, L., Weichselbaum, E., O'Connor, A., Williams, E.B., Benelam, B., Riley, H., Stanner, S., 2011. Red meat in the diet: an update. Nutr. Bull. 36, 34–77.

Zamora, F., Debiton, E., Lepetit, J., Lebert, A., Dransfield, E., Ouali, A., 1996. Predicting variability of ageing and toughness in beef M. Longissimus lumborum et thoracis. Meat Sci. 43, 321–333.

Herbipole, INRAE, 2018. Low mountain ruminant experimental facility, doi:10.15454/1.5572318050509348E12

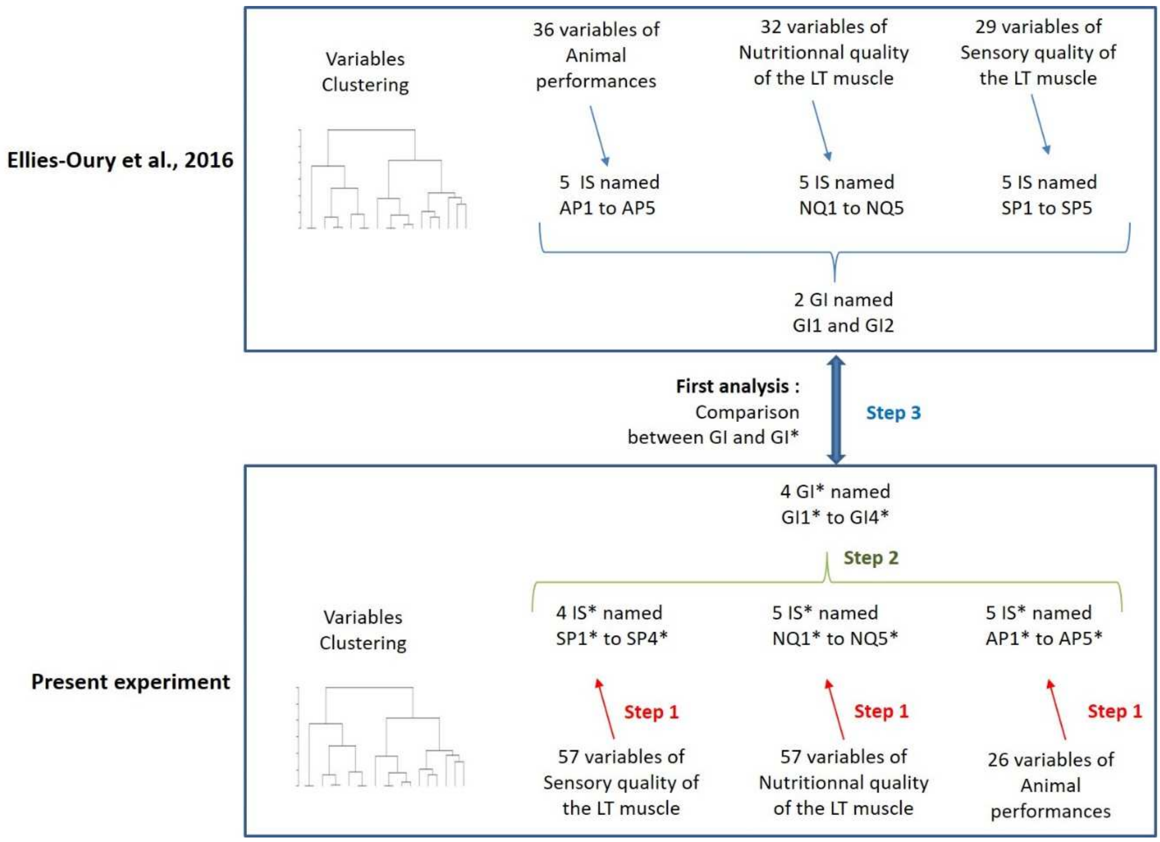

Figure 1: principle of the method developed by Ellies-Oury et al. (2016) and in the present experiment
IS: intermediate score – GI: global index – LT: *Longissimus thoracis* – AP: animal performance – NQ: nutritional quality – SQ: sensory quality

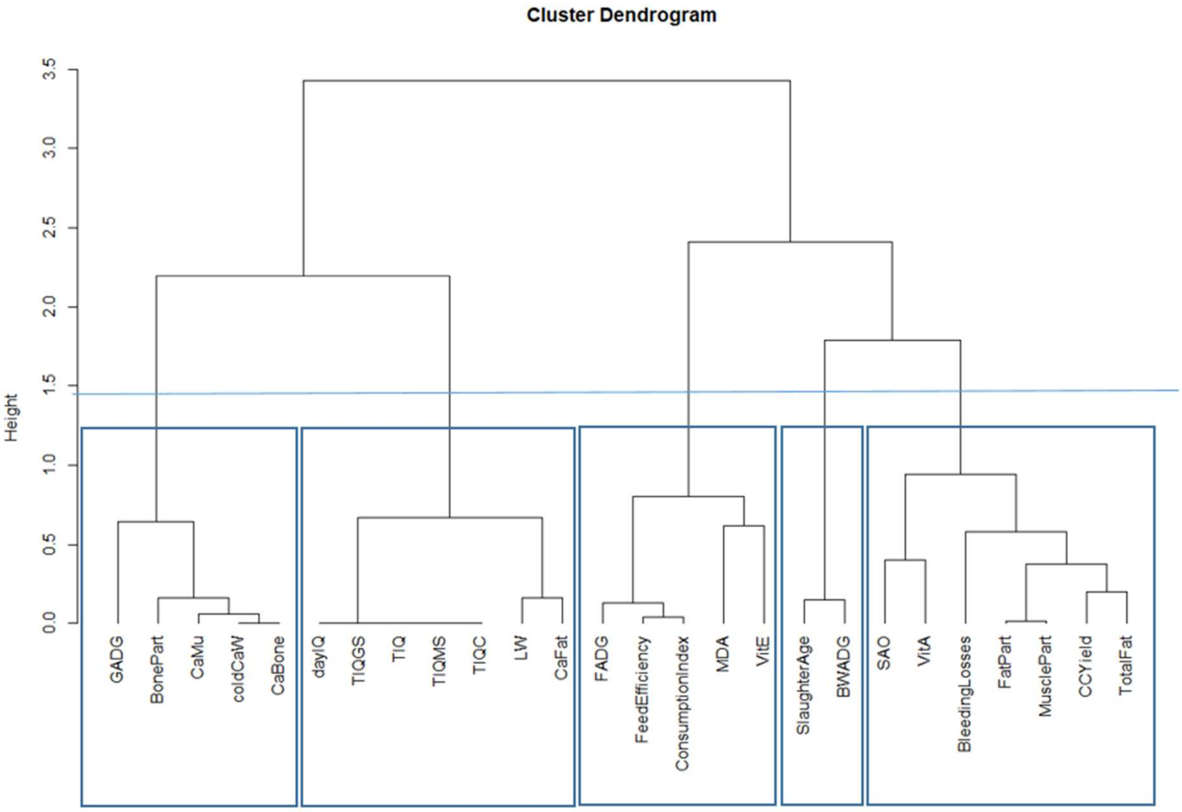

Figure 2: Intermediate Scores (n=5) retained concerning Animal Performances

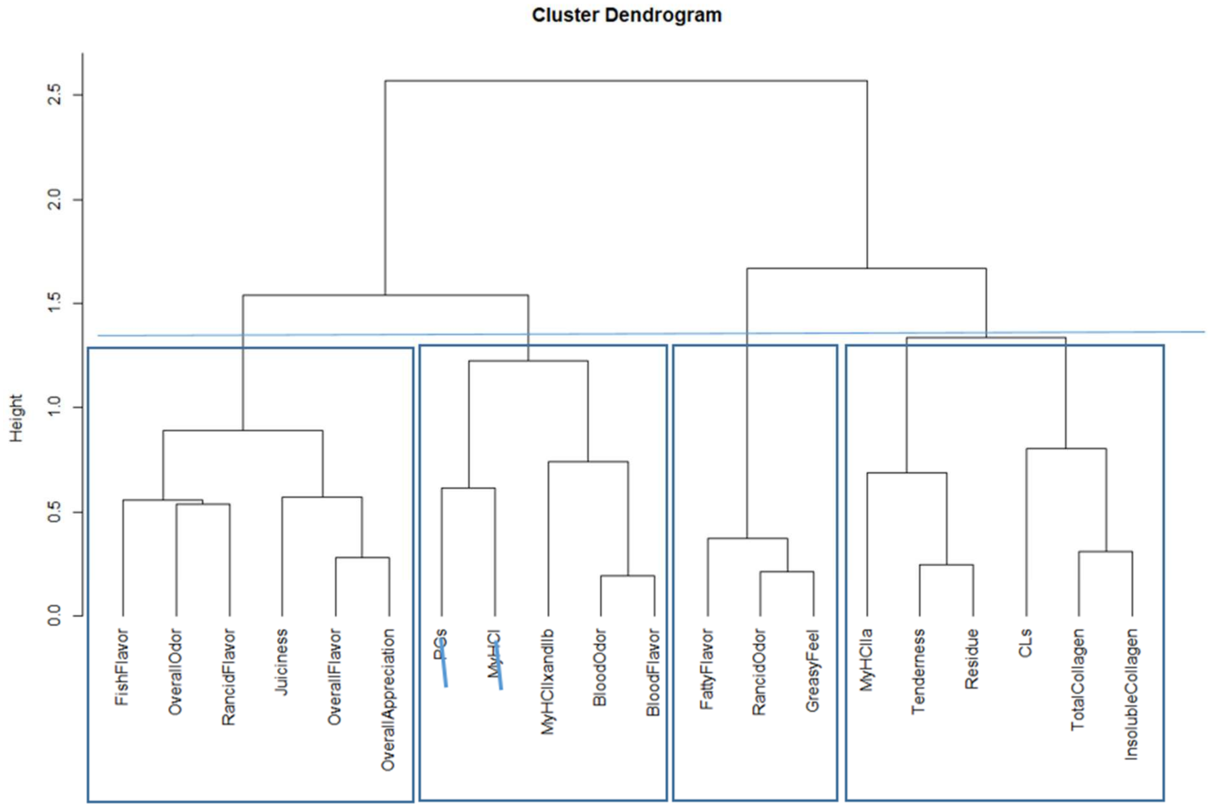

Figure 3: Intermediate Scores (n=4) retained concerning Sensorial Quality

The 2 crossed-out variables (PGs, MyHCI) correspond to variables poorly represented in the cluster (and not analyzed in the following).

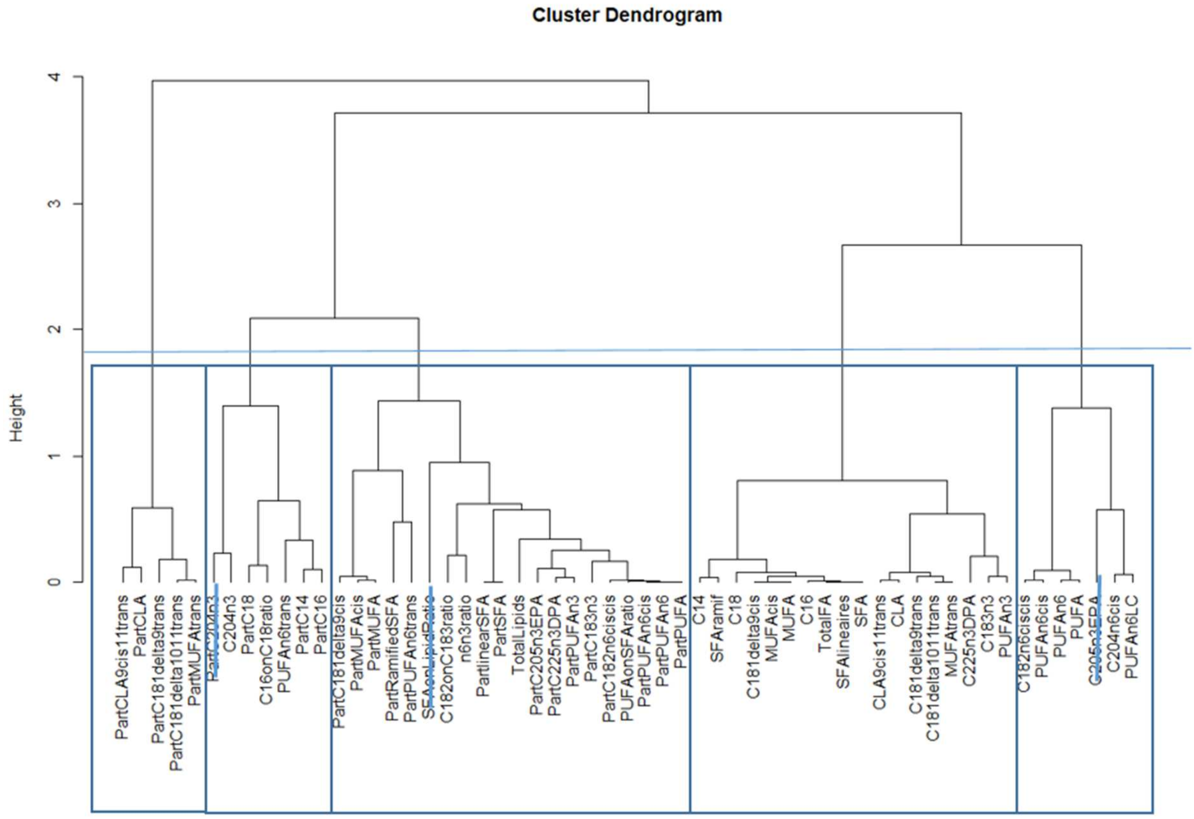

Figure 4: Intermediate Scores (n=5) retained concerning Nutritional Quality

The 3 crossed-out variables (%C20:4n3; SFA/Lipid ratio; C20:5n3EPA) correspond to variables poorly represented in the cluster (and not analyzed in the following)

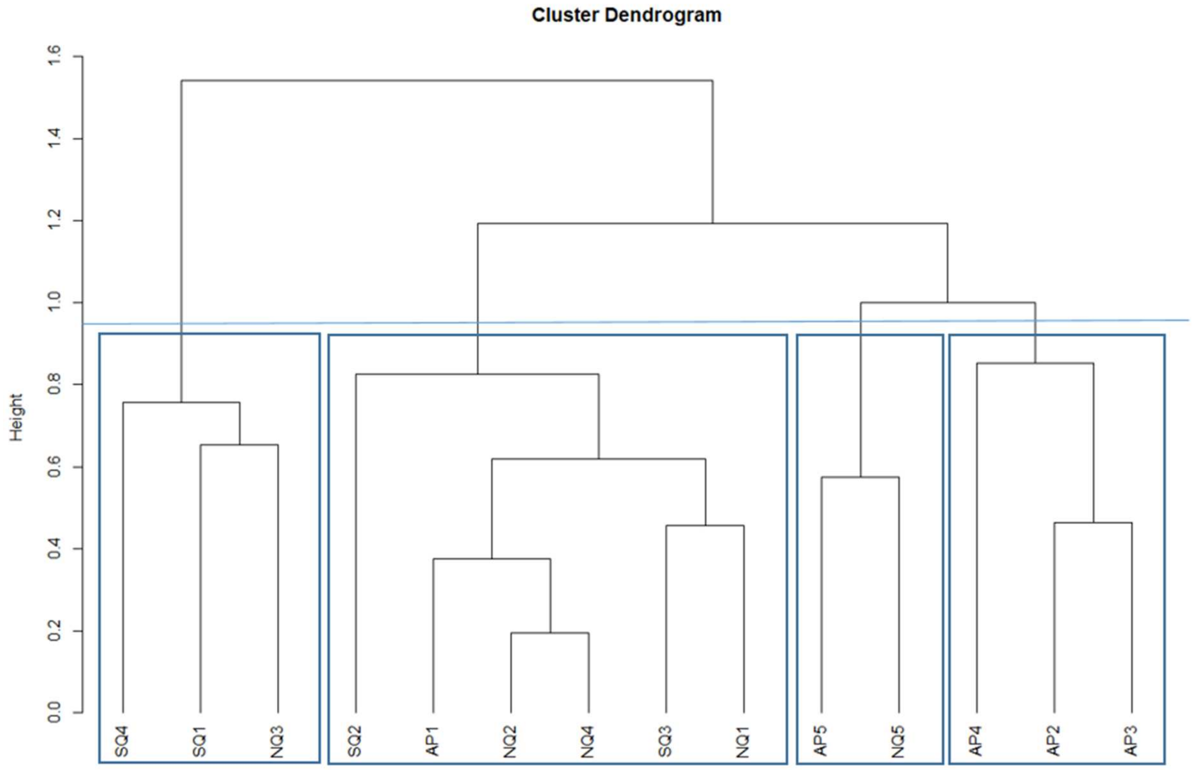

Figure 5: Global Indexes (GI) built by making clusters within Intermediate Scores
5 Intermediate Scores [denoted AP1 to AP5*] concerning Animal Performances*
4 IS concerning Sensorial Quality [SQ1 to SQ4*]*
5 IS concerning Nutritional Quality [NQ1 to NQ5*]*

Table 1: list of the 26 variables of animal performances analyzed on the 32 young Charolais bulls

Variables
Age at slaughter; Total ingested quantities in grass silage (TIQGS), maize silage (TIQMS), concentrate (TIQC); Total ingested quantities (TIQ); Ingested quantities per day (dayIQ); Live weight (LW); Carcass weight (CaW); Carcass Yield (CCYield = CaW / LW); Bleeding losses; Total fat weight (Total Fat); Carcass fat weight (CaFat); Carcass proportion of fat (FatPart); Carcass bone weight (CaBone); Carcass proportion of bone (BonePart); Carcass muscle weight (CaMuscle); Carcass proportion of muscle (MusclePart); Average Daily Gain (ADG) between birth and weaning (BWADG), during growth (GADG), and during finishing period (FADG) Feed conversion Efficiency (ADG / total dry matter intake); Consumption index (total dry matter intake / ADG) Amount in A and E vitamins; MDA; SAO

Table 2: list of the 20 variables of sensory quality analyzed on the 32 young Charolais bulls

Variables
Tenderness; Juiciness; Residue; Overall appreciation; Overall odor; Overall Flavor; Fish flavor; Blood odor; Blood flavor; Rancid odor; Rancid flavor; Fatty flavor; Greasy feel; Total collagen; Insoluble collagen; CLs; PGs; MyHC I; MyHC IIa ; MyHC IIx+b;

Table 3: list of the 57 variables of nutritional quality analyzed on the 32 young Charolais bulls

Variables
Fatty acid composition expressed in content (g or mg / 100 g of muscle): Total Lipids; Total Fatty Acids (FA); Saturated FA (SFA); Monounsaturated FA (MUFA); Polyunsaturated FA (PUFA); C14:0; C16:0; C18:0; ramified SFA; linear SFA; C18:1 n-9 cis; *trans* C18:1 10/11; *trans* C18:1 n-9; *cis* MUFA; *trans* MUFA; C18:2 n-6; *cis* C20:4 n-6; PUFA n-6; C18:3 n-3; DPA; EPA; PUFA n-3; long chain PUFA n-3; Total Conjugated Linoleic Acids (CLA); CLA 9*cis* 11*trans*; *trans* PUFA; *cis* PUFA **Fatty acid composition expressed in proportions (% of total FA):** Total Fatty Acids; Saturated FA; Monounsaturated FA; Polyunsaturated FA; C14:0; C16:0; C18:0; ramified SFA; linear SFA; C18:1 n-9 cis; C18:1 9*trans*; C18:1 10/11*trans*; *cis* MUFA; *trans* MUFA; C18:2 n-6; C20:4 n-6; PUFA n-6; *trans* PUFA n-6; *cis* PUFA n-6; C18:3 n-3; EPA; DPA; PUFA n-3; Total Conjugated Linoleic Acids; CLA 9*cis* 11*trans* **Ratios :** C16:0 / C18:0; PUFA / SFA; PUFA n-6 / PUFA n-3 ; C18:2 n-6 / C18:3 n-3

Table 4: Composition of each of the Intermediate Scores obtained for each parameter of interest (animal performances, sensorial quality and nutritional quality) in both experiment

	Ellies-Oury et al., 2016	Present experiment
Animal Performances (AP)	AP1 Fat development in the carcass and in the 5th quarter, but also total fat and trim fat	AP1* Carcass Weight, Amount of muscles/bone in the carcass, ADG during growth **Negatively linked to** Part of Bone in the carcass
	AP2 Empty body weight and bone development	AP2* Bleeding losses, Carcass yield, Part of muscle in the carcass, **Negatively linked to** Fat development in the carcass, amount in A vitamins, Part of fat in the carcass, SAO
	AP3 Feed conversion efficiency, ADG during finishing period	AP3* Feed conversion efficiency, ADG during finishing period, MDA **Negatively linked to** Consumption index, amount in E vitamins
	AP4 Viscera weight and proportions	AP4* Live weight, Amount of fat in the carcass, ingested quantities (total, per day, GS, MS, C)
	AP5 Butcher value (compactness, thigh thickness, muscle development, yields, carcass weight)	AP5* Age and ADG between birth and weaning
Sensorial Quality (SQ)	SQ1 Meat quality traits of steaks cooked at 55°C (higher tenderness and lower residue content) and/or 74°C (higher tenderness and juiciness and lower residue content)	SQ1* MyHCIIA, Residues, collagen amounts (total, insoluble) and CLs **Negatively linked to** Tenderness
	SQ2 Whiteness (L*) **Negatively linked to** yellowness (b*)	SQ2* MyHC IIX and IIB, blood odor and flavor
	SQ3 Oxidative metabolism (ICDH and COX activities and %MyHC I)	SQ3* Juiciness and Overall flavor/odor/appreciation **Negatively linked to** Rancid and fish flavors
	SQ4 Collagen content and insolubility, lipid content **Negatively linked to** glycolytic fibres proportions (MyHC IIx+IIb)	SQ4* Fatty flavor, rancid odor and greasy feel
	SQ5 Protein content	
Nutritional Quality (NQ)	NQ1 n-6/n-3 ratios (n-6/n-3 and C18:2 n-6 / C18: 3n-3)	NQ1* C16:0/C18:0, % C14:0, % C16:0, *trans* PUFA amount **Negatively linked to** % C18:0, % C20:4 n-3
	NQ2 Total lipids, Amounts of SFA, CLA and MUFA	NQ2* Lipids, % SFA, % linear SFA, % MUFA, % *cis* MUFA, % *cis* C18:1D9 **Negatively linked to** C18:2 n-6/C18:3 n-3, n6/n3, % ramified SFA, PUFA/SFA % EPA, % DPA, % n-3 PUFA, % C18:2 n-6 *cis cis*, % C18:3 n-3, % *trans* n-6 PUFA, % *cis* n-6 PUFA, % n-6 PUFA, %PUFA
	NQ3 % MUFA *trans*	NQ3* % CLA, % CLA 9*cis* 11*trans*, % C18:1 9*trans*, % C18:1 10-11*trans*, % *trans* MUFA
	NQ4 % PUFA, % n-6 PUFA, % n-3 PUFA **Negatively linked to** %SFA and %MUFA	NQ4* Amounts of FA, C14:0, C16:0, C18:0, ramified SFA, linear SFA, SFA, *cis* MUFA, MUFA, C18:1n-9 *cis*, CLA 9cis 11*trans*, CLA, C18:1 9*trans*, C18:1 10-11*trans*, *trans* MUFA, C22:5 n-3 DPA, C18:3 n-3, n-3 PUFA
	NQ5	NQ5*

	Amounts of PUFA, n-3 PUFA and n-6 PUFA	Amounts of PUFA, n-6 PUFA, long chain n-6 PUFA, *cis* n-6 PUFA, C18:2 n-6 *cis cis*, C20:4 n-6 *cis*

Table 5: Composition of each Global Index established by a clustering of the previous IS in both experiment

Ellies-Oury et al., 2016	Present experiment
GI1: + AP1 + NQ1 - SQ1 Butcher value (compactness, thigh thickness, muscle development, yields, carcass weight), % PUFA, % PUFA n-3, % PUFA n-6, Glycolytic fibres, Residues **Negatively linked to** Fat development, Non-productive needs, Lipid, SFA, MUFA, PUFA, n-3 PUFA, n-6 PUFA, % SFA, % C14:0, % C16:0, % MUFA, Tenderness (55°C and 74°C), Juiciness (74°C), Oxidative metabolism, Collagen amounts (total, insoluble)	**GI 1*: + NQ3* + SQ1* + SQ4*** % CLA, % CLA 9*cis* 11*trans*, % C18 :1 9*trans,* % C18 :1 10-11*trans*, % *trans* MUFA MyHCIIA, Residues, collagen amounts (total, insoluble) and CLs Fatty flavor, rancid odor and greasy feel **Negatively linked to** Tenderness
GI2 = + NQ2 + SQ2 % MUFA *trans*, Yellowness (b*), Protein content **Negatively linked to** Whiteness (L*), n-6 / n-3, C18:2 n-6/C18:3 n-3	**GI 2 *: + AP1* – NQ2* – NQ4* – NQ1* – SQ3* (-SQ2*)** Carcass weight, amount of muscles/bone in the carcass, ADG during growth % C18:0, % C20:4 n-3, % EPA, % DPA, %, n-3 PUFA, % C18:2 n-6 *cis cis*, % n-6 PUFA, %PUFA, % C18:3 n-3, % ramified SFA, % *cis* n-6 PUFA, % *trans* n-6 PUFA, C18:2 n-6/C18:3 n-3, n-6/n-3, PUFA/SFA, Rancid and fish flavors **Negatively linked to** C16:0/C18:0, Lipids % SFA, % C14:0, % C16:0, % linear SFA, % MUFA, % *cis* MUFA, % C18:1 n-9 *cis*; Amount of FA, C14:0, C16:0, C18:0, ramified SFA, linear SFA, SFA, *cis* MUFA, MUFA, C18:1 n-9 *cis*, CLA 9 *cis* 11 *trans*, CLA, C18:1 9*trans*, C18:1 10-11*trans*, *trans* MUFA, C22:5 n-3, C18:3 n-3, n-3 PUFA, *trans* PUFA, Juiciness and Overall flavor/odor/appreciation, Part of Bone in the carcass
	GI 3*: + NQ5* + AP4* Amount of PUFA, n-6 PUFA, long chain n-6 PUFA, *cis* n-6 PUFA, C18:2 n-6 *cis cis*, C20:4 n-6 *cis* Age and ADG between birth and weaning
	GI 4*: + AP3* + AP2* + AP5* Live weight, amount of fat in the carcass, Ingested quantities, Bleeding losses, Carcass yield, Part of muscle in the carcass, Feed conversion efficiency, ADG during finishing period, MDA **Negatively linked to** Fat development in the carcass, Part of fat in the carcass, Consumption index, Amount in A and E vitamins, SAO