What is the impact of the rearing management applied during the heifers' whole life on the toughness of five raw rib muscles in relation with carcass traits?

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Abstract

The aims of this study were, analysing the effects of rearing managements, carcass traits, and muscle type (M. *complexus* [CP], M. *infraspinatus* [IF], M. *longissimus* [LM], M. *rhomboideus* [RH], and M. *serratus ventralis* [SV]) on toughness of raw meat; developing prediction models to act on their toughness. According to our results obtained on the data of 77 heifers, the IF raw muscle was the toughest and appeared the most sensitive to a change in the rearing management. The four other raw muscles had a similar toughness within heifers from the same rearing management. The five raw muscles were less tough when the carcass was heavier and had higher dressing percentage and conformation. The 3 models explained about 40% of the variability observed. Our models showed that it is possible to improve the potential tenderness of raw meat, acting on: age of the heifer's mother, growth rate during the growth and fattening periods, slaughter age, carcass weight and temperature 24h *post-mortem.*

1 Introduction

For consumers, the tenderness is the main expectation to purchase beef meat (Henchion et al., 2014). However, this quality trait is highly variable according to many factors related to (i) muscle properties (*e.g.* structural, metabolic, and contractile properties) (S.-H. Joo et al., 2017; Listrat et al., 2020; Oury et al., 2010; Picard & Gagaoua, 2020; Totland & Kryvi, 1991; Veiseth-Kent et al., 2018), (ii) animal type (*e.g.* breed, gender) (Bures & Barton, 2012; Chambaz et al., 2003; Christensen et al., 2011; Gagaoua et al., 2016a), and (iii) technological process (*e.g.* aging or cooking conditions) (Aviles et al., 2015; Gagaoua et al., 2016b). Moreover, many studies showed that others factors as rearing managements (Couvreur et al., 2019; Soulat et al., 2020) or carcass traits (Gagaoua et al., 2019; Soulat et al., 2020) had an impact on the final tenderness of meat. Few works had studied the effect of these factors on the toughness of raw meat, illustrating the tenderness potential of muscles (Christensen et al., 2011; Ellies-Oury et al., 2012, 2017; Purchas & Zou, 2008). Furthermore, the studies of the literature about the impact of rearing management on meat tenderness (on raw or cooked meat) were mainly on M. *longissimus* (LM) considered as the reference muscle and concerned mainly the fattening period. The toughness (raw meat) or the tenderness (cooked meat) of the other muscles of the rib was weakly studied (Gruber et al., 2006; Soulat et al., 2019; Veiseth-Kent et al., 2018). To our knowledge, no study of the literature analysed jointly the effects of rearing managements and carcass traits on the toughness of several raw muscles of the rib.

However, when the consumers purchase and eat ribs or short ribs, several muscles with different properties and levels of quality compose the wholesale cuts. Consequently, in the present study we considered the main five muscles constituting the rib from the chuck sale section. As the cooking conditions could be different according to countries or the consumer tastes (rare, medium-rare or well-cooked) and had an impact on the final tenderness of meat (Gagaoua et al., 2016b), we chose to evaluate the toughness of aged meat on raw muscles to be in conditions as close as possible to those of the consumer when he buys the meat. Moreover, we considered the rearing management applied during the heifers' whole life and not only during the fattening period as in Soulat et al. (2020). So, the first aim of this work was to analyse the effect of rearing managements, carcass quality, and their interaction on the toughness measured by Warner-Bratzler shear force, of five raw rib muscles: M. *complexus* (CP), M. *infraspinatus* (IF), LM, M. *rhomboideus* (RH), and M. *serratus ventralis* (SV). The second aim was to identify rearing factors and/or carcass traits that could be used to manage simultaneously the toughness of these five raw muscles.

2 Material and methods

2.1 Animals, rearing managements, slaughtering and carcass traits

This study used 77 crossed Charolais x Aubrac heifers from eight commercial farms. Surveys were performed to collect 46 rearing factors (Tables 1 to 3) characterizing three key periods of the whole heifers' life (from birth to slaughter): pre-weaning (PWP), growth period (GP) and fattening period (FP) (Soulat et al., 2018a). Then, the four rearing managements (RM) described by Soulat et al. (2020) were used in this study. The main characteristics of these RM are summarized in the Fig. 1.

The 77 heifers were slaughtered in the same industrial slaughterhouse (Abattoir du Gévaudan, Antrenas, France). Six carcass traits were collected: cold carcass weight (calculated from the measured hot carcass weight x 0.98, kg), dressing percentage (ratio of cold carcass weight to live weight before slaughter, %), conformation and fat scores using the EUROP system (EC, 2006) and the pH and the temperature at 24 h *post-mortem* (pH 24h and Temp 24h, respectively) (Table 4). In the EUROP system, the conformation score is divided into five ordered classes (E = very high; to P = very poor muscle development). Moreover, each class has three subdivisions (high: "+", average: "=", and low: "-"). The fat score is divided into five ordered classes (1 = lean; to 5 = very fat). All carcasses of this study had a fat score of 3, consequently this parameter was not considered.

The two carcass quality clusters (CARCA-Low and CARCA-High) described by Soulat et al. (2020) were used in this study. The carcasses in CARCA-High had significantly higher cold weight, and dressing percentage than those in CARCA-Low. Moreover, the CARCA-High cluster was composed mainly by carcasses of the classes U+ and U=, whereas the CARCA-Low cluster was composed by carcasses of the classes U- and R+.

2.2 Muscle sampling and meat quality trait

Two beef ribs (the 5th and the 4th) of each carcass were collected, at 24 h *post-mortem*, as described in Soulat et al. (2020). Then, each beef rib sample (n = 77) was individually vacuum-packaged and aged for 14 days at 4 °C. After, these samples were frozen and stored at -20 °C until the analyses.

After thawing of the beef rib samples (around 48h), the shear force was measured on five muscles: CP, IF, LM, RH, and SV, using a Warner-Braztler apparatus (EZ-SX set assay EU RoHS, Shimadzu, Kyoto, Japan). For each beef rib samples, the five muscles were dissected and meat portions (length: 1.5 to 3 cm; width: 1 cm; and thickness: 0.5 to 1 cm) were cut. The shear force was measured cutting perpendicularly to the fibers of the raw meat portions (least five portions) obtained and calculated using the Trapezium X 1-5.1 software (Shimadzu, Kyoto, Japan) (Wheeler et al., 1997).

For each muscle, the data of shear force are presented in the Table 4.

2.3 Statistical analyses

Statistical analyses were performed using R 4.0.0 software (R core Team, 2020). The statistical procedures performed in this work were summarized in the Fig. 2.

2.3.1 Descriptive statistical analyses

For the shear force, an ANOVA with random effects (mixed model) was performed to evaluate its dependence on the RM, the carcass quality cluster and the muscle. The fixed effects were: RM, carcass quality, muscle, RM x muscle interaction, and carcass quality x muscle interaction; and the random effect was: animal. If an interaction was not significant in the ANOVA, a new ANOVA was performed without this interaction in the model. Then, if the results of the mixed model were significant, a Tukey test was performed. The mixed model was performed using the "lmerTest" (Kuznetsova et al., 2017) package and the Tukey test was carried out using the "emmeans" (Lenth, 2020) and "multcompView" (Graves et al., 2019) packages.

A principal component analysis (PCA) was performed to illustrate the relationships between the shear force values of the 5 muscles, using the "FactoMineR" (Le et al., 2008) package.

2.3.1 Predictive statistical analyses

Before establishing the models of prediction, a first step was performed to test the multicollinearity between the 46 rearing factors (Fig. 2). The multicollinearity was tested using the variance inflation factors (VIF) calculated from the "car" package (Fox & Weisberg, 2019). As explained by Soulat et al. (2018a), the explicative variables with the greatest VIF were removed one by one, to finally obtain explicative variables with VIF < 10.

After this step, 19 rearing factors were retained (these rearing factors are described in Tables 1 to 3, in bold):

- Rearing factors for the pre-weaning period ($p = 10$):
    - Birth weight
    - Age of the heifer's mother at the heifer's birth (age of the cow)
    - Age of the heifer's mother at first calving
    - Pre-weaning duration
    - Total time spent by the calf with her mother between the birth and the weaning
    - Insemination type (artificial or natural)
    - Calving (intervention or not of the farmer during the calving)
    - Calculated average of the concentrates' crude protein in the diet during PWP
    - Average daily gain (ADG) of the calf between the birth and the weaning
    - Offered or not concentrates in housing calf diet during PWP
- Rearing factors for the growth period ($p = 2$):
    - ADG between the weaning and the beginning of the fattening period
    - Nature of pasture (during the pasture, heifers diet was complemented by hay or not).
- Rearing factors for the fattening period ($p = 7$):
    - Slaughter age
    - ADG between the beginning of FP and the slaughter

- Calculation of the grass silage percentage in the average diet across the whole FP
- Calculation of the wrapped haylage percentage in the average diet across the whole FP
- Calculated average of the forage's crude protein content across the whole FP
- Calculated average of the forage's net energy content across the whole FP
- Calculated average of the concentrate's net energy content the whole FP

This process was similarly performed on the carcass traits (p = 5) which all had VIF < 10.

Three linear models were developed to predict the shear force (SF) of the 5 muscles. The first one (RF_SF) was obtained from the selected rearing factors, the second one (CARCA_SF) from the carcass data, and the last one (RF&CARCA_SF) from the selected rearing factors and the carcass data (Fig. 2).

To obtain our final prediction models, the procedure described in Soulat et al. (2018a) was applied. For example, initially in the complete RF_SF model, all rearing factors selected and the muscle factor were included. Then, the non-significant rearing factors were removed one by one to obtain the simplest prediction model. After each withdrawal, using a probability ratio test, the new model was compared with the previous model. If the result of the comparison between 2 models was $P < 0.10$, the independent variable was conserved (Fig. 2).

As an external validation of the prediction models was not possible with the number of animals in our dataset, the validation of each model was performed using the bootstrap procedure (Tan et al., 2006). For each developed model, this procedure was repeated 500 times to generate 500 bootstrap samples. After the bootstrap procedure, the mean coefficient of each independent variable was calculated. The number of times the coefficients of the independent variables in the model were significant was counted over the 500 repetitions.

To evaluate the quality of the prediction models, three criteria were considered to describe the robustness of the model from the root mean square errors of prediction (RMSEP, (Kobayashi & Salam, 2000)), the accuracy of the model from the mean prediction error (MPE, (Yan et al., 2007)), and the precision of the model from the coefficient of determination (R^2). In this study, the RMSEP, MPE, and R^2 were calculated at each repetition of the bootstrap. Then, the mean of these three criteria was calculated. As in Bonnet et al. (2020), the developed models were considered to have a high or good accuracy when MPE ranged from 0.10 to 0.30 and to have a high precision when R^2 was the closest to 1. To compare the different prediction models, the Akaike information criterion (AIC) was also calculated. The best model has the lowest calculated AIC, RMSEP, and MPE values and the highest R^2 value.

3 Results and discussion

3.1. Effects of the rearing managements, muscle, and carcass quality clusters on the toughness of raw aged meat

According to our results, the interaction between the rearing management and muscle, and the carcass clusters had a significant effect on the toughness of the raw meat (Table 5). The toughness of the CP, LM, RH, and SV muscles was not significantly different when the heifers received the same rearing management (Fig. 3). In cattle, the RH and SV muscles are postural muscles, the LM is a support muscle, and the CP muscle is involved in the movement of the animal's head (Totland & Kryvi, 1991; University of Nebraska-Lincoln, 2020). The muscle fiber characteristics could be impacted by the muscle type (S. T. Joo et al., 2013; Picard & Gagaoua, 2020; Totland & Kryvi, 1991). However, the location and the function of these 5 muscles did not seem to have an impact on their toughness. The toughness of IF muscle, which is also a postural muscle, was the highest among the 5 muscles and the most sensitive to changes in rearing managements. More precisely, the IF muscle was tougher for heifers from RM-4 than for those from RM-2 and RM-3 (Fig. 3). According to the traits of the 4 rearing managements described in Soulat et al. (2020) and used in this work, the main differences between RM-4 and both rearing managements 2 and 3 were:

- During PWP, the calves from RM-4 had higher average daily gain and pasture duration than those from RM-2 and RM-3
- During GP, the heifers from RM-4 had lower number of days of offered concentrates in the diet and lower pasture duration than those from RM-2 and RM-3. The average concentrate's crude protein and net energy contents (calculated across the whole growth period) were lower in RM-4 than in RM-2 and RM-3.
- During FP, the fattening of heifers from RM-4 was performed at pasture. In this rearing management, the heifers were older at the beginning of their fattening than those from RM-2 and RM-3. The heifers from RM-4 had lower concentrate intake during this period than those from RM-2 and RM-3. The average forage's crude protein and neutral detergent fiber contents (calculated across the whole fattening period) were lower in RM-4 than in RM-2 and RM-3.

In the literature, there are few works which studied the effects of several rearing factors on the toughness of raw meat. Moreover, there are also few works which studied the effects of rearing factors applied before the fattening period on the meat tenderness. These results were obtained on cooked meat making it difficult to compare to ours results.

Hennessy et al. (2001) observed that the tenderness of LM was lower when calves had a quick growth before weaning. In our study, the calves from the RM-4 had a quicker growth before weaning than those from RM-2 and RM-3. However, the toughness of raw LM was similar for these 3 rearing managements (Fig. 3). In our study, the animals were slaughtered older than those in Hennessy et al. (2001). No significant differences were observed between these 3 rearing managements for the other muscles except for the raw IF muscle. It was possible that the slaughter age mitigated the effect of the growth rate before weaning, except on the toughness of IF. Modzelewska-Kapitula & Nogalski (2016) showed that the proportion of fat in the raw IF muscle was significantly higher when the young bulls had a quick growth during their fattening. The growth speed of animal could had an impact more or less important according to the muscle.

During the growth period, Miller et al. (1987) did not observe an effect of the diet's energetic level on the tenderness of LM, M. semimembranosus, and M. semitendinosus cooked meat. It could be possible that the IF muscle was more sensitive to this factor than these three muscles.

During the fattening period, the heifers consumed variable concentrate quantities according to the rearing management. However, many studies did not observe an effect of the concentrate quantity in the fattening diet on the tenderness of LM after cooking (French et al., 2001; Keady et al., 2013; Moloney & Drennan, 2013). Moreover, during their life, the heifers from the RM-4 had the longest pasture duration, consequently these heifers had a higher physical activity than those in housing. According to the results of Cozzi et al. (2010), the LM after cooking was tougher when heifers performed their fattening at pasture. This result could partly explain why the raw IF muscle is tougher for heifers from the RM-4. The physical activity could have an effect on the connective tissue and/or the myofibril integrity of this muscle. The results of Modzelewska-Kapitula & Nogalski (2016) showed that the fattening diet had not a significant effect on the tenderness of IF muscle after cooking, in young bulls fattening in a free-stall. However, for the LM, Pordomingo et al. (2012) did not observe an effect of the fattening type (pasture *vs.* housing) on the meat tenderness, in heifers.

In accordance with previous results, the difference of IF toughness observed between the rearing managements could not be explained by one rearing factor (Soulat et al., 2020; 2018b).

Moreover, the raw IF muscle was also tougher than the four other muscles regardless of the rearing management (Fig. 3). After 24h *post-mortem*, Torrescano et al. (2003) observed also that the raw IF muscle was tougher than the raw LM. The IF muscle is an oxidative muscle and contained a higher proportion of type I fibers (79%) and a lower proportion of type IIA and IIX fibers than LM, SV, and RH (Totland & Kryvi, 1991). The IF muscle is one of the major postural muscles in the forepart with mean size of type I above 4000 µm² and IIX between 2000 and 2500 µm², respectively (Totland & Kryvi, 1991). The mean size of type I fibers of SV muscle was also above 4000 µm², whereas, the mean size of type IIX fibers was between 3000 and 3500 µm². For the LM, the size of type I and IIX fibres was below 3100 µm² and above 3800 µm² (Jurie et al., 2005, 2007). According to the results of Torrescano et al. (2003), the IF muscle had more insoluble collagen than the raw LM, without aging. After aging, the IF muscle had lower myofibrillar fragmentation index, higher sarcomere length, proportion of intramuscular fat, collagen level, and pH 48h than LM (Purchas & Zou, 2008; Veiseth-Kent et al., 2018). These different traits between the IF and the others rib's muscles could explain the difference of toughness observed for the raw meat.

The result of the PCA showed that the tenderness of IF muscle was less correlated with the tenderness of the other four muscles (Fig. 4). However, the shear force values of the 5 muscles were positively correlated.

Only for heifers from RM-2, the LM was more tender than CP and RH muscles, without cooking (Fig. 3). The main differences of the RM-2 with the 3 other were during the fattening period (Fig. 1). Briefly, the heifers from RM-2 were lighter and younger at the beginning of the fattening with a fattening outside without pasture. Moreover, the fattening duration was the longest and the quantity of concentrate intake was the highest. In accordance with our results, Thenard et al. (2006) observed also that the raw RH muscle was tougher than the LM. According to these authors, the RH muscle had higher total collagen and lower proportion of soluble collagen than LM. The RH contained a higher proportion of type I fibers and a lower proportion of type IIA fibers than LM (Totland & Kryvi, 1991).The toughness difference observed between both muscles could be mainly explained by the muscle traits. To our knowledge, there are no works studying the toughness of raw CP. However, the RH was tougher than CP after cooking (Bratcher et al., 2005).

The five raw muscles were the tougher for CARCA-Low cluster (Table 5). According to Soulat et al. (2020) and Gagaoua et al. (2019), the carcass traits can be linked to a higher overall tenderness. The heavier carcasses with higher dressing percentage and conformation produced raw LM and M. *rectus abdominis* (RA) more tender, in heifers (Ellies-Oury et al., 2017; Soulat et al., 2020). For cooked meat, Gagaoua et al. (2019) observed that the LM had the highest tenderness when the carcasses had a fat score ≥ 2.42, a cold carcass weight < 419 kg, and a dressing percentage ≥ 60%. However, Couvreur et al. (2019) did not observe difference on the tenderness of LM in cull cows between both clusters: Ylight (young and light cows) and Yheavy (young and heavy cows), after cooking. Moreover, after 14 days of aging, Ellies-Oury et al. (2017) and Agbeniga & Webb (2018) did not observe an effect of cold carcass weight on the tenderness of RA and LM muscles, respectively.

3.2. Identification of rearing factors and carcass traits to reduce the toughness of the five raw aged rib's muscles

In this work, three models were proposed to predict the shear force of the five-aged rib's muscles. In the RF_SF and CARCA_ SF models, the shear force was only predicted from rearing factors or carcass traits, respectively. In the RF&CARCA_SF, the shear force was predicted from rearing factors and carcass traits. The parameters of prediction quality (AIC, R^2 and MPE) of these three models were similar (Table 6). However, these models explained only about 40% of the shear force's variability observed.

According to the coefficient of the independent variables in the 3 models, if one of these variables was increased, the raw meat was low tough.

In the RF_SF model, the independent variables considered were age of the cow, the ADG during GP and FP, and the slaughter age (Table 6).

To our knowledge, the effect of the age of the cow on the meat toughness has not been studied. It is possible that the physiological stage, the genetic and/or the epigenetic of the cow influence the meat toughness of this progeny.

Contrary to our results, Hennessy et al. (2001) observed a decreased of LM tenderness when the calves had high ADG before weaning. In our study, heifers were slaughtered older than cattle in Hennessy et al. (2001). Although the slaughter age was less often significant in the RF_SF model compared to the three others independent variables, this rearing factors had an impact on the toughness. In accordance with Soulat et al. (2018a) for the RA, the slaughter of older heifers allowed to have a tenderness meat higher. Ahnstrom et al. (2012) and Bures & Barton (2012) observed also an increase of the LM tenderness when the heifers were slaughtered older.

The raw meat from these five muscles is potentially less tough if the heifer's mother is an older cow, if the heifer has a quick growth during GP and FP, and/or if the heifer is slaughtered older.

In the CARCA_SF model, the independent variables considered in the model were the cold weight and Temp 24h of the carcass (Table 6). In accordance with our results, Ellies-Oury et al. (2017) observed that the raw RA was more tender when the carcasses were heavier, in heifers. After cooking, these authors did not observe an effect of carcass weight on the tenderness of RA muscle. According to the results of Agbeniga & Webb (2018), the LM from heavy carcasses was also more tender than those from light carcasses after 3 days of aging and cooking. However, no effect of the carcass weight was observed on the LM tenderness after 14 days of aging, by these authors. Moreover, some studies observed that the LM was significantly more tender when the young bulls or steers were slaughter heavier (Keane & Allen, 1998; Sañudo et al., 2004). In our model CARCA_SF, Temp 24h of the carcass had an effect on the toughness of the raw meat. According to our results, the carcasses with a slow chilling produce a raw meat low tough. This result reinforces that the shear force of LM increased with a quick chilling of the carcass (Mao et al., 2012; Zhang et al., 2019).

Our results displayed that the heavier carcasses with a Temp 24h higher increased the potential to obtain raw meat low tough, independently of the rearing management.

When both rearing factors and carcass traits are considered simultaneously in the RF&CARCA_SF model, the independent variables included in the model were age of the cow and the cold weight and the temperature at 24h of the carcass (Table 6). In this model, we found independent variables considered in RF_SF and CARCA_SF. However, the simultaneous consideration of the rearing factors and the carcass traits did not allow to an improvement in the prediction quality of the five muscles' shear force.

For the same prediction quality of the shear force, the CARCA_SF model seems to be the simplest model to implement because its independent variables are easily recoverable at the slaughterhouse. However, the RM_SF appeared also interesting to manage the tenderness potential of raw meat early.

4. Conclusion

These results showed that the 4 rearing managements applied during the heifers' whole life did not significantly impact the toughness of the raw CP, LM, RH, and SV muscles. They displayed that the toughness of the raw IF muscle was higher and more sensitive to the rearing management than the other muscles. Moreover, the toughness of the five muscles was lower when the carcass was heavier and had higher dressing percentage and conformation score.

Our results displayed also some rearing factors (age of the cow, ADG during GP and FP, and slaughter age) and some carcass traits (cold carcass weight and Temp 24h) which could be used as lever to improve the potential tenderness of the 5 raw rib's muscles studied. Consequently, these data highlighted that it could be possible to manage simultaneously the tenderness potential of different rib's muscles during the animals' life. This work can contribute to study the potential tenderness of meat to help the beef sector (from the farm to the plate of consumer) to improve the quality of meat products by adaptation of the rearing system.

In complement to this work, it would be interesting to study the effects of the rearing managements and carcass traits on the tenderness of cooked meat to precise the effect of cooking on the potential tenderness, and to analyse others muscles from the same carcass to evaluate the quality of many meat cuts.

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List of figures

Fig. 1. Summary of the four rearing managements applied during the heifers' whole life defined by Soulat et al. (2020) (ADG = average daily gain; Tot_duration_CC = total time spent by the calf with her mother between the birth and the weaning; Conc_duration = number of days of offered concentrates in the diet; Conc_quanti_intake = average daily quantity intake per heifer, Conc_NE = calculated average of concentrate's net energy content; Conc_CP = calculated average of concentrate's crude protein content; Forage_CP = calculated average of the forage's crude protein content; Forage_NDF = calculated average of the forage's neutral detergent fiber content).

Fig. 2. Framework of the statistical procedures performed in this study: descriptive and predictive analyses. (RF: rearing factor, CARCA: carcass, SF: shear force)

Fig. 3. Effect of the interaction between the rearing managements (RM) and the muscles (M. *complexus*, CP; M. *infraspinatus*, IF; M. *longissimus*, LM; M. *rhomboideus*, RH; and M. *serratus ventralis*, SV) on the shear force of raw meat. [a,b,c,d,e,f]Estimated marginal means (emmeans) in different letters were significantly different ($P < 0.05$).

Fig. 4. Principal component analysis of shear force of the raw five rib's muscles (M. *complexus*, CP; M. *infraspinatus*, IF; M. *longissimus*, LM; M. *rhomboideus*, RH; and M. *serratus ventralis*, SV).

Table 1

Description of the rearing factors characterizing the pre-weaning period (PWP) (in bold, the rearing factors conserved after the test of multicollinearity).

Pre-weaning period				
Quantitative rearing factors	Description of the rearing factor	Mean ± SE[1]	Min	Max
Age of the cow (year)	Age of the heifer's mother at the heifer's birth	6.9 ± 0.3	2.6	14.0
Age at the first calving (month)	Age of the heifer's mother at first calving	34.4 ± 0.3	26.0	38.0
Birth weight (kg)	Calf weight at birth	41 ± 0.5	28	53.0
ADG_PWP (kg/day)	Average daily gain of the calf between the birth and the weaning	1.0 ± 0.02	0.6	1.3
Duration_day_CC (hour/day)	Time spent per day by the calf with her mother during the housing period	12.1 ± 1.3	0.3	24.0
Tot_duration_CC (day)	Total time spent by the calf with her mother between the birth and the weaning	194.0 ± 7.9	110.9	305.0
Conc_duration_PWP (day)	Number of days of offered concentrates in the diet during PWP	83.8 ± 7.2	0.0	236.0
Conc_CP_PWP (g/kg DM[2])	Calculated average of the concentrates' crude protein in the diet during PWP	98.7 ± 6.5	0.0	264.3
Conc_NE_PWP (day)	Calculated average of the concentrates' net energy in the diet during PWP	0.8 ± 0.1	0.0	1.8
Pasture_duration_PWP (day)	Numbers of days spend at pasture during PWP	143.2 ± 2.8	107.0	174.0
PWP_duration (day)	Number of days between the birth and the weaning of the calf	254.7 ± 3.7	156.0	306.0

Qualitative rearing factors	Modalities of the rearing factors	Description of the rearing factor	n
Insemination type			
	Artificial	Artificial insemination using frozen semen	37
	Natural	Insemination performed by a bull	40
Calving			
	Easy	Natural calving	61
	Help	Farmer intervention during the calving	16
Bull type			
	Bull-3y	3-year-old bulls belonging to the farmer	25
	Bull->3	Bull older than 3 years belonging to the farmer	23
	Bull-IA-CE	Artificial insemination from frozen semen for calving ease	9
	Bull-IA-EM	Artificial insemination from frozen semen for early maturity	8
	Bull-IA-CE&EM	Artificial insemination from frozen semen for calving ease and early maturity	12
Conc_housing_PWP			
	Yes	Offered concentrates in housing calve diet during PWP	66
	No	No offered concentrates in housing calve diet during PWP	11
Conc_pasture_PWP (%)			

	Yes	Offered concentrates in pasture calve diet during PWP	17
	No	No offered concentrates in pasture calve diet during PWP	60

[1] SE = standard error.

[2] DM = dry matter.

Table 2

Description of the rearing factors characterizing the growth period (GP) (in bold, the rearing factors conserved after the test of multicollinearity).

Growth period					
Quantitative rearing factors	Description of the rearing factor		Mean ± SE[1]	Min	Max
Age at the weaning (month)	Age of heifer at the weaning		8.5 ± 0.1	5.2	10.1
Weaning weight (kg)	Heifer weight at the weaning		291 ± 12.7	168	374
ADG_GP (kg/day)	Average daily gain of the heifer between the weaning and the beginning of the fattening period		0.6 ± 0.01	0.3	0.8
Conc_quanti_intake_GP (kg)	Total concentrate quantity intake per heifer during the GP		290.9 ± 27.7	45.9	845.5
Conc_duration_GP (day)	Number of days of offered concentrates in the diet during GP		207.5 ± 13.5	51.0	407.0
Conc_CP_GP (g/kg DM[2])	Calculated average of concentrate's crude protein content across the whole GP		98.35 ± 6.7	12.62	187.6
Conc_NE_GP (Mcal/kg DM)	Calculated average of concentrate's net energy content across the whole GP		0.9 ± 0.1	0.2	1.9
Pasture_duration_GP (day)	Number of days spend at pasture during GP		275.1 ± 6.2	197.0	349.0
Qualitative rearing factors	Modalities of the rearing factors	Description of the rearing factor			n
Hay_GP (%)					
	< 20%	Across the whole GP, the calculated average percentage of hay in the housing diet was below 20%			10
	[20%; 40%[	Across the whole GP, the calculated average percentage of hay in the housing diet was between 20% and 40% not included			31
	[40%; 80%]	Across the whole GP, the calculated average percentage of hay in the housing diet was between 40% and 80%			19
	> 80%	Across the whole GP, the calculated average percentage of hay in the housing diet was above 80%			17
Grass_silage_GP (%)					
	0%	Across the whole GP, the heifers had not grass silage in the housing diet			42
	< 50%	Across the whole GP, the calculated average percentage of grass silage in the housing diet was below 50%			8
	> 50%	Across the whole GP, the calculated average percentage of grass silage in the housing diet was above 50%			27
Wrapped_haylage_GP (%)					
	0%	Across the GP, the heifers had not wrapped haylage in the housing diet			41
	< 40%	Across the GP, the calculated average percentage of wrapped haylage in the housing diet was below 40%			10
	[40%; 60%]	Across the GP, the calculated average percentage of wrapped haylage in the housing diet was between 40% and 60%			14
	> 60%	Across the GP, the calculated average percentage of wrapped haylage in the housing diet was above 60%			12
GP_duration (day)					
	< 500 days	The number of days between the weaning and the beginning of the fattening was below 500 days			16
	> 500 days	The number of days between the weaning and the beginning of the fattening was above 500 days			61
Nature of pasture					
	Grass	During above 75% of the pasture period, the heifer diet was only grass			58

Grass & Hay	During above 75% of the pasture period, the heifer diet was grass and a hay complement	19

[1] SE = standard error.

[2] DM = dry matter.

Table 3

Description of the rearing factors characterizing the fattening period (FP) (in bold, the rearing factors conserved after the test of multicollinearity).

Fattening period					
Quantitative rearing factors	Description of the rearing factor		Mean ± SE[1]	Min	Max
Age early fattening (month)	Age of the heifer at the beginning of FP		27.7 ± 0.3	20.4	30.3
Initial weight (kg)	Live weight of the heifer at the beginning of FP		606 ± 6.7	448	779
Slaughter age (month)	Age of the heifer at the slaughter		32.8 ± 0.3	28.3	37.3
Slaughter weight (kg)	Live weight of the heifer before the slaughter		727 ± 6.9	590	873
ADG_FP (kg/day)	Average daily gain of the heifer between the beginning of FP and the slaughter		0.7 ± 0.03	0.19	2.4
Hay_FP (%)	Calculation of the hay percentage in the average diet across the whole FP		55.4 ± 4.1	17.2	100
Grass_silage_FP (%)	Calculation of the grass silage percentage in the average diet across the whole FP		22.0 ± 2.8	0.0	82.8
Wrapped_haylage_FP (%)	Calculation of the wrapped haylage percentage in the average diet across the whole FP		21.7 ± 2.8	0.0	64.6
Forage_CP_FP (g/kg DM[2])	Calculated average of the forage's[3] crude protein content across the whole FP		110.6 ± 3.2	14.4	143.7
Forage_NE_FP (Mcal/kg DM)	Calculated average of the forage's[3] net energy content across the whole FP		1.2 ± 0.01	1.0	1.3
Forage_NDF_FP (g/kg DM)	Calculated average of the forage's[3] neutral detergent fiber (NDF) content across the whole FP		572.6 ± 5.2	510.2	642.3
Conc_quanti_intake_FP (kg/day)	Total quantity intake per heifer during FP		786.4 ± 55.5	97.3	1967.4
Conc_NE_FA (Mcal/kg DM)	Calculated average of the concentrate's net energy content the whole FP		1.9 ± 0.01	1.6	2.0
Pasture_duration_FP (day)	Number of days spend at pasture during FP		53.3 ± 8.3	0.0	199.0
FP_duration (day)	Number of days between the beginning of FP and the slaughter		47.0 ± 15.0	201.5	605.0
Qualitative rearing factors	Modalities of the rearing factors	Description of the rearing factor			n
Conc_CP_FP (g/kg DM)					
	< 250 g/kg DM	Across the whole FP, the calculated average of concentrate's crude protein content was below 250 g/kg DM			59
	> 250 g/kg DM	Across the whole FP, the calculated average of concentrate's crude protein content was above 250 g/kg DM			18
Fattening system					
	Housing	The fattening was carried out in housing			33
	Pasture	The fattening was carried out at pasture			15
	Pasture & Housing	The fattening was started at pasture and then finished in housing			14
	Outside	The fattening was carried out outside without grass			15

[1] SE = standard error.

[2] DM = dry matter.

[3] Forage = hay + grass silage + wrapped haylage.

Table 4

Description of the carcass traits and the shear force of the five rib's muscles.

Carcass traits			
Quantitative rearing factors	Mean ± SE[1]	Min	Max
Cold weight (kg)	425 ± 4.79	330	509
Dressing percentage (%)	58.5 ± 0.24	53.6	65.6
Temperature at 24 h (°C)	6.8 ± 0.11	4.0	9.6
Qualitative carcass traits	Modalities of the carcass traits		n
Number of carcasses per EUROP class[2]			
	E-		3
	U+		24
	U=		28
	U-		16
	R+		6
pH 24 h			
	< 5.8		22
	≥ 5.8		55
Meat traits			
Shear force (N/cm²)	Mean ± SE	Min	Max
M. *complexus*	60.8 ± 1.75	27.9	110.3
M. *infraspinatus*	90.7 ± 3.08	45.5	162.4
M. *longissimus*	45.2 ± 1.43	23.7	88.5
M. *rhomboideus*	61.1 ± 1.99	13.3	112.9
M. *serratus ventralis*	54.1 ± 1.88	31.2	125.3

[1] SE = standard error.

[2] The EUROP classes are E+ (extremely muscled), E=, E-, […], P+, P=, and P- (very poorly muscled).

Table 5

Effects of the rearing managements, carcass clusters, muscle and their interaction on the toughness of the meat.

	Shear force (N/cm²)	
	Emmean[1]	SE[2]
Rearing management[3] (RM)		
RM-1	63.2	2.51
RM-2	64.3	3.01
RM-3	60.8	2.36
RM-4	68.7	2.36
Carcass clusters[4] (C)		
CARCA-Low	67.9	2.52
CARCA-High	60.6	1.41
Muscles (M)		
M. *complexus*	62.6	2.16
M. *infraspinatus*	92.6	2.19
M. *longissimus*	46.8	2.16
M. *rhomboideus*	63.0	2.16
M. *serratus ventralis*	56.2	2.17
P-value		
RM	0.13	
C	0.01	
M	< 0.001	
M x RM	0.007	

[1] Emmean = estimated marginal means.

[2] SE = standard error.

[3] Rearing managements = the four rearing managements considered were defined and described in Soulat et al. (2020).

[4] Carcass clusters = carcass clusters' traits were defined and described in Soulat et al. (2020).

Table 6

Equations and performances for the three linear prediction models of shear force (RF_SF model established from only rearing factors, CARCA_SF model established from only carcass traits, and RF&CARCA_SF model established from rearing factors and carcass traits).

Models	Independent variables[1]	Coefficients (± SD)	N of significant variables over 500 bootstraps[2]	RMSEP[3]		R^2		MPE[4]		AIC[5]	
				Mean	CI[6]	Mean	CI	Mean	CI	Mean	CI
RF_SF				18.10	[16.33; 19.91]	0.43	[0.33; 0.52]	0.29	[0.27; 0.32]	3274.89	[3208.68; 3332.71]
	Intercept	127.4 ± 18.5									
	M. *infraspinatus*	30.1 ± 3.4									
	M. *longissimus*	-15.5 ± 2.1									
	M. *rhomboideus*	0.3 ± 2.5									
	M. *serratus ventralis*	-6.6 ± 2.4									
	Age of the cow	-0.9 ± 0.3	426								
	ADG_GP	-22.6 ± 6.5	461								
	Slaughter age	-1.0 ± 0.4	323								
	ADG_FP	-8.5 ± 2.8	412								
CARCA_SF				17.85	[15.96; 19.70]	0.44	[0.34; 0.53]	0.29	[0.26; 0.31]	3270.30	[3204.22; 3326.68]
	Intercept	122.7 ± 11.7									
	M. *infraspinatus*	30.2 ± 3.4									
	M. *longissimus*	-15.6 ± 2.1									
	M. *rhomboideus*	0.2 ± 2.4									
	M. *serratus ventralis*	-6.7 ± 2.5									
	Cold carcass weight	-0.1 ± 0.03	496								
	Temperature at 24 h	-2.0 ± 1.0	294								
RF&CARCA_SF				17.89	[16.07; 19.68]	0.44	[0.35; 0.53]	0.29	[0.26; 0.31]	3259.63	[3200.82; 3313.81]

Intercept	128.1 ± 11.7	
M. *infraspinatus*	30.2 ± 3.6	
M. *longissimus*	-15.4 ± 2.2	
M. *rhomboideus*	0.5 ± 2.5	
M. *serratus ventralis*	-6.5 ± 2.6	
Age of the cow	-0.8 ± 0.3	372
Cold carcass weight	-0.1 ± 0.02	499
Temperature at 24 h	-2.0 ± 1.0	316

[1] For the explanation of the models' independent variables please refer to the following tables: Tables 1 to 3 for the rearing factors, and Table 4 for the carcass traits.

[2] Number of times the independent variables were significant in the model over 500 bootstraps.

[3] RMSEP = root mean square error of prediction.

[4] MPE = mean prediction error.

[5] AIC = Akaike information criterion.

[6] CI = confidence interval.

Fig. 1. Summary of the four rearing managements applied during the heifers' whole life defined by Soulat et al. (2020) (ADG = average daily gain; Tot_duration_CC = total time spent by the calf with her mother between the birth and the weaning; Conc_duration = number of days of offered concentrates in the diet; Conc_quanti_intake = average daily quantity intake per heifer, Conc_NE = calculated average of concentrate's net energy content; Conc_CP = calculated average of concentrate's crude protein content; Forage_CP = calculated average of the forage's crude protein content; Forage_NDF = calculated average of the forage's neutral detergent fiber content).

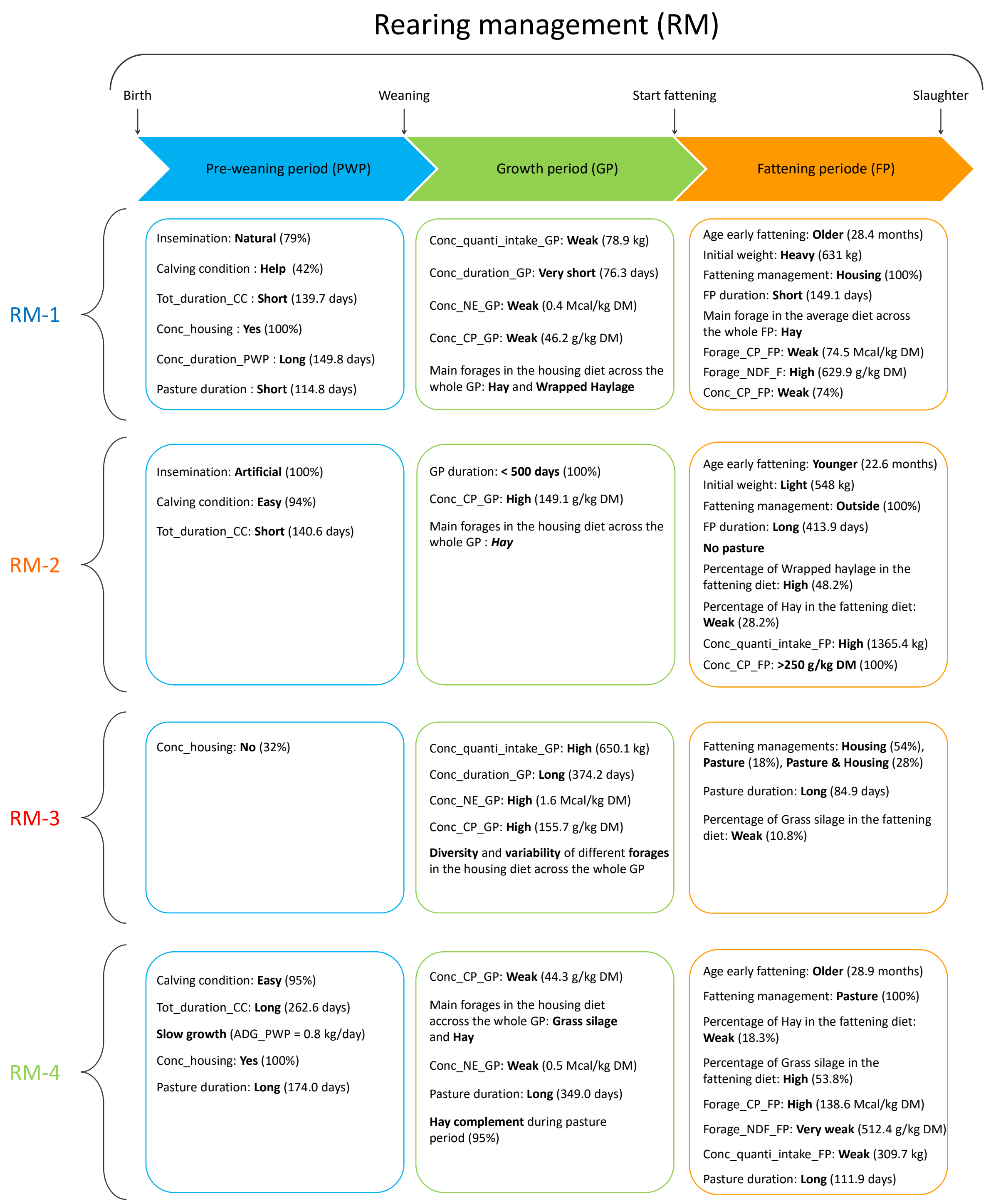
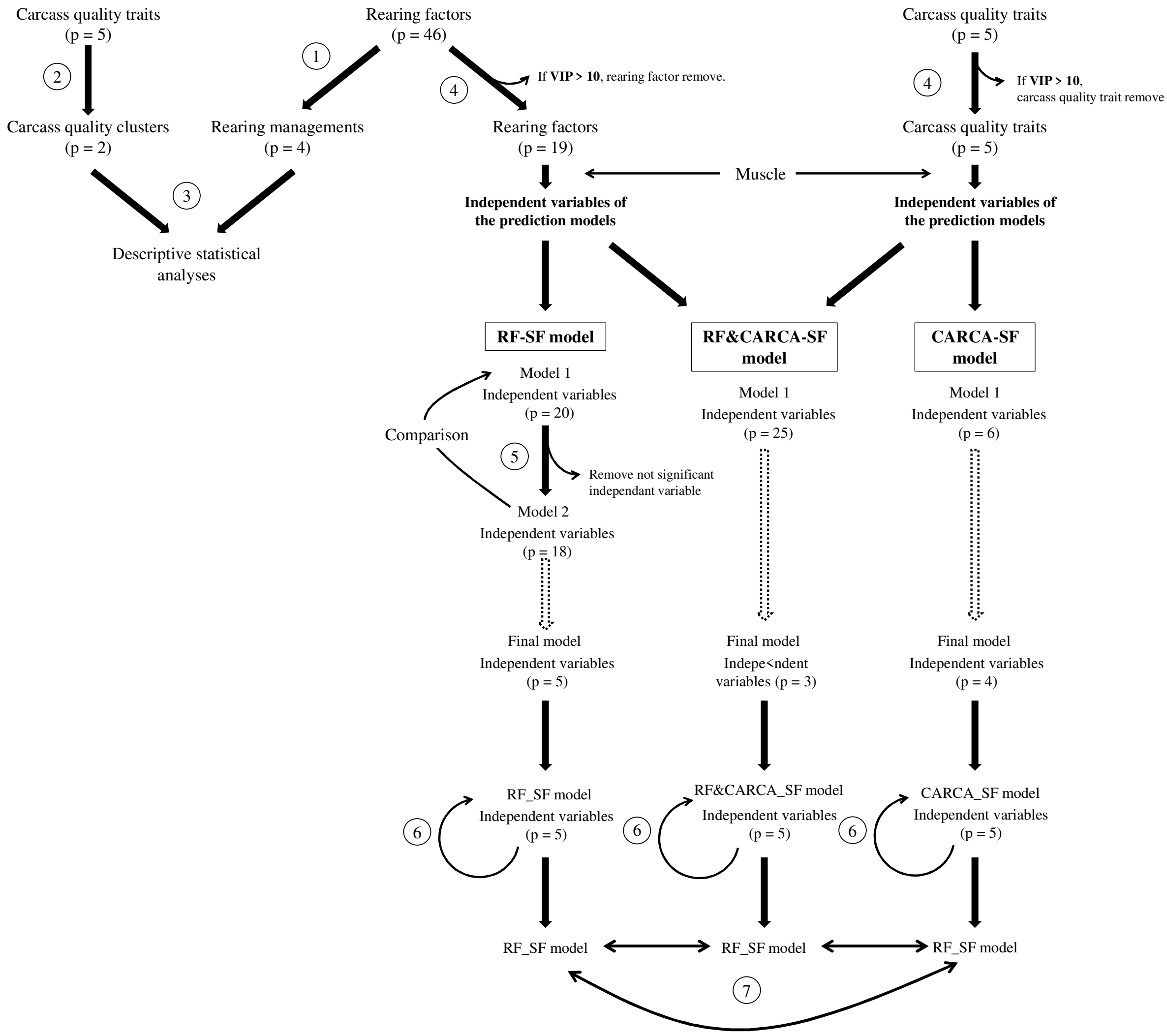

Rearing management (RM)
Birth
Weaning
Start fattening
Slaughter
Pre-weaning period (PWP)
Growth period (GP)
Fattening periode (FP)
RM-1
Insemination: **Natural** (79%)
Calving condition : **Help** (42%)
Tot_duration_CC : **Short** (139.7 days)
Conc_housing : **Yes** (100%)
Conc_duration_PWP : **Long** (149.8 days)
Pasture duration : **Short** (114.8 days)
Conc_quanti_intake_GP: **Weak** (78.9 kg)
Conc_duration_GP: **Very short** (76.3 days)
Conc_NE_GP: **Weak** (0.4 Mcal/kg DM)
Conc_CP_GP: **Weak** (46.2 g/kg DM)
Main forages in the housing diet across the whole GP: **Hay** and **Wrapped Haylage**
Age early fattening: **Older** (28.4 months)
Initial weight: **Heavy** (631 kg)
Fattening management: **Housing** (100%)
FP duration: **Short** (149.1 days)
Main forage in the average diet across the whole FP: **Hay**
Forage_CP_FP: **Weak** (74.5 Mcal/kg DM)
Forage_NDF_F: **High** (629.9 g/kg DM)
Conc_CP_FP: **Weak** (74%)
RM-2
Insemination: **Artificial** (100%)
Calving condition: **Easy** (94%)
Tot_duration_CC: **Short** (140.6 days)
GP duration: **< 500 days** (100%)
Conc_CP_GP: **High** (149.1 g/kg DM)
Main forages in the housing diet across the whole GP : ***Hay***
Age early fattening: **Younger** (22.6 months)
Initial weight: **Light** (548 kg)
Fattening management: **Outside** (100%)
FP duration: **Long** (413.9 days)
No pasture
Percentage of Wrapped haylage in the fattening diet: **High** (48.2%)
Percentage of Hay in the fattening diet: **Weak** (28.2%)
Conc_quanti_intake_FP: **High** (1365.4 kg)
Conc_CP_FP: **>250 g/kg DM** (100%)
RM-3
Conc_housing: **No** (32%)
Conc_quanti_intake_GP: **High** (650.1 kg)
Conc_duration_GP: **Long** (374.2 days)
Conc_NE_GP: **High** (1.6 Mcal/kg DM)
Conc_CP_GP: **High** (155.7 g/kg DM)
Diversity and **variability** of different **forages** in the housing diet across the whole GP
Fattening managements: **Housing** (54%), **Pasture** (18%), **Pasture & Housing** (28%)
Pasture duration: **Long** (84.9 days)
Percentage of Grass silage in the fattening diet: **Weak** (10.8%)
RM-4
Calving condition: **Easy** (95%)
Tot_duration_CC: **Long** (262.6 days)
Slow growth (ADG_PWP = 0.8 kg/day)
Conc_housing: **Yes** (100%)
Pasture duration: **Long** (174.0 days)
Conc_CP_GP: **Weak** (44.3 g/kg DM)
Main forages in the housing diet accross the whole GP: **Grass silage** and **Hay**
Conc_NE_GP: **Weak** (0.5 Mcal/kg DM)
Pasture duration: **Long** (349.0 days)
Hay complement during pasture period (95%)
Age early fattening: **Older** (28.9 months)
Fattening management: **Pasture** (100%)
Percentage of Hay in the fattening diet: **Weak** (18.3%)
Percentage of Grass silage in the fattening diet: **High** (53.8%)
Forage_CP_FP: **High** (138.6 Mcal/kg DM)
Forage_NDF_FP: **Very weak** (512.4 g/kg DM)
Conc_quanti_intake_FP: **Weak** (309.7 kg)
Pasture duration: **Long** (111.9 days)

Fig. 2. Framework of the statistical procedures performed in this study: descriptive and predictive analyses (RF: rearing factor, CARCA: carcass, SF: shear force).



Descriptive analyses

1. Determination of the rearing managements (using a **factor analysis for mixed data** following then a **hierarchical clustering on principal components**).
2. Determination of the carcass quality clusters (using a **factor analysis for mixed data** following then a **hierarchical clustering on principal components**).
3. Performing of the ANOVA.

Predictive analyses

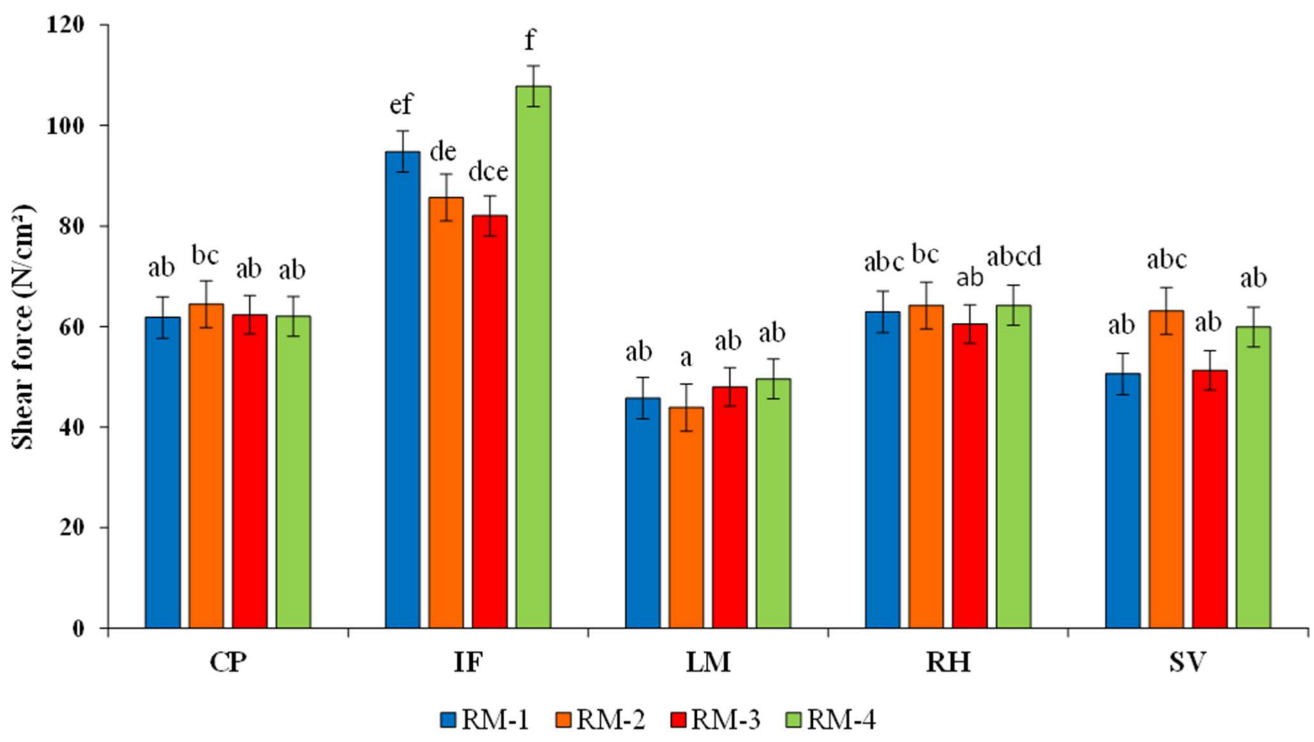
4. Multicollinearity test (using the variance inflation factors, **VIF**).
5. Establishment of the prediction model (using **linear regression**).

   - If $Model_a = Model_{a+1}$, the independant variable could be removed.
   - If $Model_a \neq Model_{a+1}$, the independent variable could not be removed.
6. Validation of the prediction model (using **bootstrap**).
7. Comparison of prediction quality between RF_SF, RF&CARCA_SF, and CARCA_SF models (using the following parameters: R², RMSEP, MPE, and AIC).

⇨ The point 5 was repeated to the final model.

p : number of parameters/variables inclued.

Fig. 3. Effect of the interaction between the rearing managements (RM) and the muscles (M. *complexus*, CP; M. *infraspinatus*, IF; M. *longissimus*, LM; M. *rhomboideus*, RH; and M. *serratus ventralis*, SV) on the shear force of raw meat. [a,b,c,d,e,f]Estimated marginal means (emmeans) in different letters were significantly different ($P < 0.05$).



Shear force (N/cm²)
120
100
80
60
40
20
0
ab
bc
ab
ab
ef
de
dce
f
ab
a
ab
ab
abc
bc
ab
abcd
ab
abc
ab
ab
CP
IF
LM
RH
SV
RM-1
RM-2
RM-3
RM-4

Fig. 4. Principal component analysis of shear force of the raw five rib's muscles (M. *complexus*, CP; M. *infraspinatus*, IF; M. *longissimus*, LM; M. *rhomboideus*, RH; and M. *serratus ventralis*, SV).