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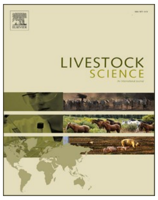

Residual feed intake for Australian Merino sheep estimated in less than 42 days of trial

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HIGHLIGHTS

- There is an increase in body weight and feed intake along the trials.
- The best correlations for average daily gain within of models was greater than 0.94.
- The feed intake correlations presented values greater than 0.93.
- The greater R-square for residual feed estimate was equal at 0.753.
- The best reduced model is the linear with 35 days.

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ABSTRACT

The evaluation of sheep feed intake (FI) in feed efficiency tests is expensive. Decreasing the test period could be a resource-saving tool by reducing the cost of evaluating each animal and allowing to test a greater number of animals per year. For this reason, the objective of this research was to explore residual feed intake (RFI) models and to decreasing the test duration. Data was collected from 286 Australian Merino sheep of three performed trials, the test period consisted of 56 days (14 days of feed and facilities adaptation and 42 days of FI and average daily gain (ADG) evaluation). Two models were used to calculate RFI, Model 1 (based on Koch et al. (1963) linear model) and Model 2 (repeated measures, weekly model). Model 1 included ADG and FI estimates in a linear regression. The second model included weekly average FI as repeated measure and the weekly ADG. The increase in body weight during the test period was not perfectly linear, presenting a marked variance increase in two of the three tests while FI presented a tendency to increase throughout of the evaluation period, however presenting a high variance per day. In the 42-days tests, Pearson and Spearman correlations between models for ADG were of 0.89 and 0.87, respectively. The best correlations were detected for FI between 42 and 35-days models, presenting Pearson and Spearman correlations of 0.95 and 0.94 in the linear model, and 0.96 and 0.95 in the weekly model. When considering RFI, the correlations between linear and weekly 42-days models were from 0.93 to 0.92, respectively. The 35-days RFI length models (linear and weekly) presented a Pearson and Spearman correlations greater than 0.98 with the 42-days models. Therefore, the RFI models 35-days of duration allowed to decrease seven days of the FI test while maintaining accuracy and explaining 75.3% of the FI in the linear model, and 63.6% of the weekly model. Reducing seven days of testing would provide a greater data collection into a year of phenotypic evaluation.

1. Introduction

Understanding the role of feed intake (FI) and growth rate in feed efficiency is indispensable to select economically efficient sheep. Moreover, it is necessary to optimize FI tests without losing precision in order to increase feed efficiency selection intensity. Increasing the

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number of animals tested without rising trial costs would also provide a faster genetic progress. The development of selection procedures, however, is challenging as increasing growth rate without increasing FI is genetically difficult (Cammack et al., 2005). Daily measurement of body weight (BW) will contribute to decrease the days on trial by monitoring the weight variance over the test and identifying more efficient and responsive animals. Furthermore, it will contribute to achieve fewer errors on data modeling. In this context, Cantalapiedra-Hijar et al. (2018) presented two different metrics for feed efficiency: feed conversion ratio (FCR), a relation between the amount of feed consumed and the animal bodyweight gain, and residual feed intake (RFI), the difference between actual and expected FI, the later based on feed requirements for maintenance and production (bodyweight gain). Although FCR is a useful index to evaluate management practices in production efficiency, it remains a ratio trait, and from a genetic point of view, selecting for FCR could cause unwanted correlated responses (Zetouni et al., 2017). Theoretically, this does not happens with RFI, since it is an independent BW and bodyweight gain measure, allowing to select animals that consume less without compromising the body size, and neither the bodyweight gain (Koch et al., 1963). As RFI is a hereditary trait, the selection for low RFI can be a useful tool to identify more lucrative animals, without affecting BW traits. The RFI heritability coefficients range from 0.11 to 0.49 in sheep (Cammack et al., 2005; François et al., 2006, 2002; Tortereau et al., 2019).

Typically, testing periods for ewes consist of 56 days: 14 days for adaptation to diet and facilities, and 42 days of evaluation period (Cammack et al., 2005; Johnson et al., 2015b, 2016, 2017; Leymaster et al., 2002; Snowder and Van Vleck, 2002; Tortereau et al., 2019). The possibility of reducing the test period with better use of data generated would minimize the costs without compromising accuracy (Archer et al., 1997) Macleay et al. (2016). and Paganoni et al. (2017) showed that it is possible to accurately evaluate sheep FI in 35 days or even less. According to that, our hypothesis is that the test period could be shortened by a week or more. It could be possible by applying a linear model that includes the daily BW measure or weight gain calculation by week and using the FI as a repeated measure, according to the approach used for Cockrum et al. (2013) and Johnson et al. (2016). Besides decreasing the days in the test without compromising the ranking of the animals (phenotypically ordered for RFI) could increase the accuracy estimates. The objective of this research was to test two alternative models of RFI to find out which one allows the reduction of days on feed intake test without losing accuracy in the identification of phenotypically efficient animals.

2. Methods

Three experiments were conducted with Australian Merino Sheep, the experimental site was located at La Magnolia Experiment Unit (National Agricultural Research Institute of Uruguay), Tacuarembó, Uruguay. Records were collected on 286 Australian Merino Sheep (143 males and 143 females), the offspring of 12 sires. The study dataset comes from three feed intake trials carried out in different periods of the year 2019, with the start dates of the evaluations, respectively, 04–29–2019, 06–17–2019, and 08–12–2019 for the trials 1, 2 and 3. The average age of animals on test per trial was 227±49, 287±48 and 339 ±48 days old in trial 1, 2 and 3, respectively. The animal's pre-test average BW was of 33.9 ± 5.6, 41.3 ± 5.4 and 36.2 ± 5.0 kg, for trial 1, 2 and 3, respectively (Fig. 2). The total precipitation, daily average temperature, and average thermal amplitude were 101.6 mm, 14.5 °C and 8.2 °C, 132.1 mm, 12.3 °C and 9.6 °C, and 210.7 mm, 12.4 °C and 10.5 °C, for trial 1, 2 and 3, respectively (data from: http://www.inia.uy/gras/Clima/Banco-datos-agroclimatico/).

All protocols applied were approved by INIA Animal Ethics Committee (INIA 2018.2), furthermore, according with Animal Research: Reporting of In Vivo Experiments (ARRIVE) guidelines and following U.K. Animals (Scientific Procedures) Act, 1986 and associated guidelines, EU Directive 2010/63/EU for animal experiments.

2.1. Data edition

For BW data, animals with sanitary problems, outliers, and biologically unlikely data were removed from the study, remaining 56,872 BW records (Trial 1 = 17,825; trial 2 = 18,660; trial 3 = 20,387; Fig. 3).

For ADG, two calculations were estimated, the first using linear regression and the second by inferring weekly gain calculation. The linear ADG was estimated using PROC REG of software SAS on 12,159 average BW (trial 1 = 3790; trial 2 = 3942; and trial 3 = 4427) considering the average BW per day-animal as dependent variable and the days on evaluation as independent variable. The model corresponded to:

$$Y = \beta_0 + \beta_1 X$$

where Y = daily BW (kg); β_0 = regression intercept; β_1 = ADG (kg/day); and X = experimental day. For the weekly ADG, the calculation was done through considering the difference in average BW of week $Y + 1$ minus the average BW in the week Y, divided by seven. The linear ADG estimate generated only one value per animal, while weekly inferences generated six values.

For feed intake, the average data of 12,225 fresh feed intake was used (3822; 3997; and 4406 average data for trials 1,2 and 3, respectively). The dry matter feed intake was obtained by multiplying the fresh feed intake data by the percentage of dry matter (after drying it in $a < 60$ °C air force oven for 72 h) of Festin®. Data considered as biologically unlikely was excluded remaining 1422,445 fresh feed intake data (447,559; 490,491; and 484,395 feed intake data for trials 1,2 and 3, respectively. The feed bin visits data presented 1441,475 events, (450,596; 499,490; and 491,389 data for trials 1,2 and 3, respectively).

In summary, the FI and BW were estimated with records considering different length of the test: 42, 35, 28, and 21 days on trial. For the linear models the average values of FI and BW for each respective period were calculated, and for the weekly models, 6, 5, 4, and 3 weekly average values were considered. For the linear ADG the estimates by linear regression on 42, 35, 28, and 21 days on trial were used, while 6, 5, 4 and 3 weekly ADG measures were utilized in the weekly models.

2.2. Feed intake trials

After 7 days of acclimatation to the new feed, the animals were allocated to one of five automated feeding systems (pens) in accordance with the BW, sex, type of birth and sire. One day after arriving, the introduction to the new feed started. Animals were fed ad libitum with Festin® (Lucerne haylage; DM, 53.73%; crude protein, 21.9%; NDF, 36.1%; ADF, 29.3%). At day 3, electronic radio frequency identification tags (RFID tagged) were applied in the animals' ears. Each pen had five individual automated feeders and two automatic weighing platforms, which were equipped with an electronic tag reader, precision scale, and connected to a central computer (Fig. 1), this allowed the control of body weight and feed intake of the animals in a daily basis. At the day 7, the entrance into collective pens was allowed after deworming.

Daily monitoring was applied by a software system that identified the entry of animals into the feeder and the body weighting platform lectures. The equipment and software were provided by Intergado (Belo Horizonte, MG, Brazil). The RFID tagged allows the identification of a specific animal at the feed bin and, consequently, their intake based on the difference in feed weight before and after the visit. The capacity of the feed bin load cells was of 200 kg (±0.025 kg of accuracy) and its dimensions were 758.4 mm x 536 mm, x 371 mm. The body weighing platform was set in the water bins where a similar sensor to the feed bins system was present, each time the animal accessed it the BW was automatically recorded. The capacity of the body weighing platform was 400 ± 0.1 kg and its dimensions were 430 mm x 1200 mm x 1200 mm.

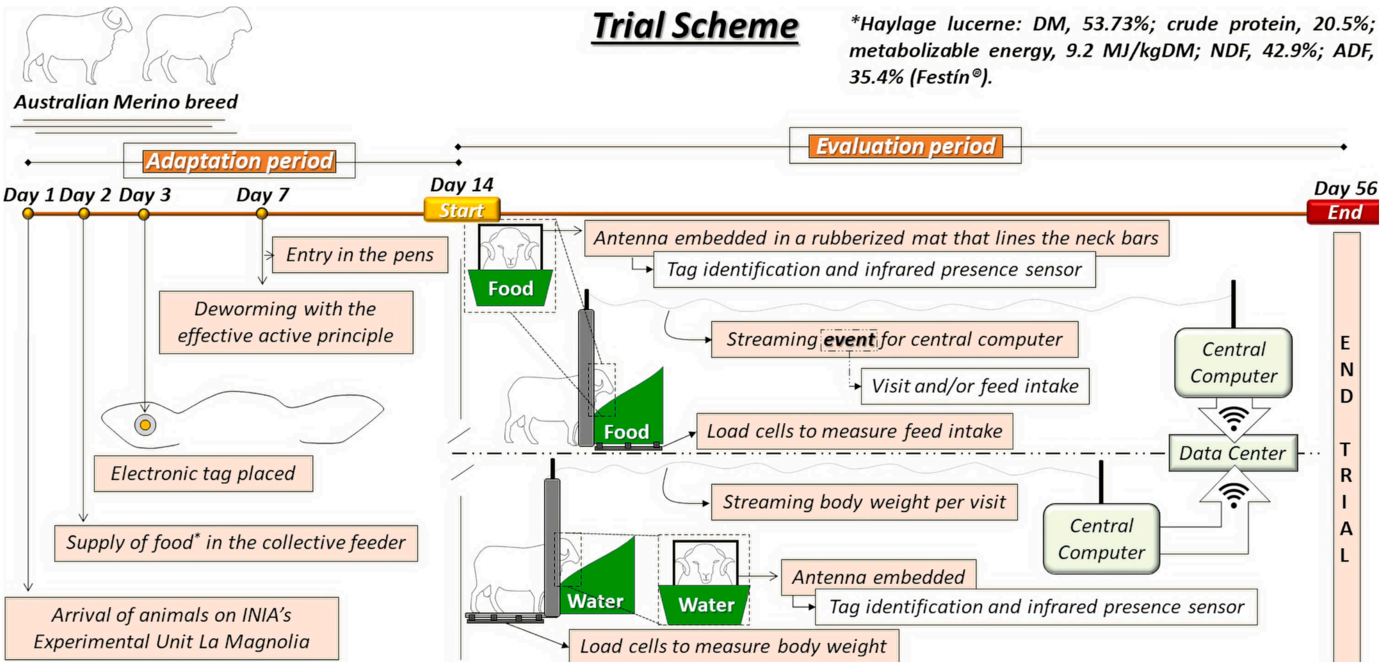
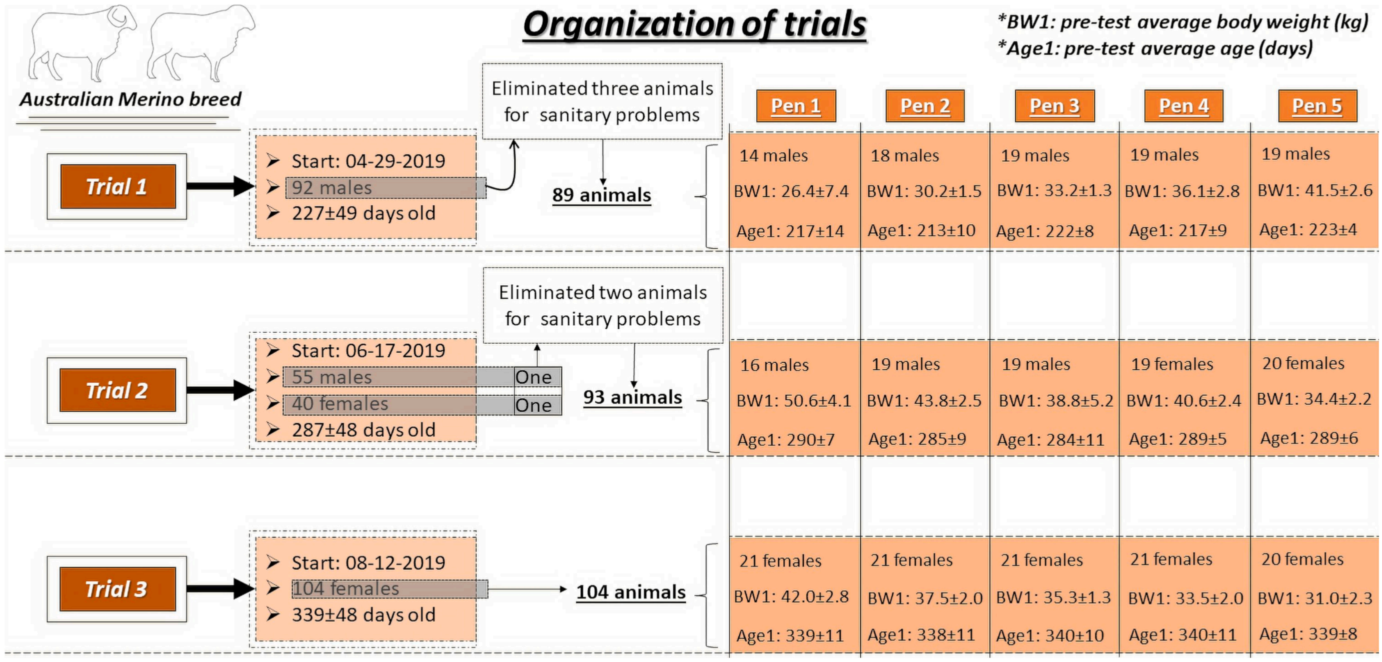


Fig. 1. Adaptation period of 14 days, with the first seven days of the feed adaptation and the rest of the feed and facilities adaptation. The evaluation period was from day 14 to day 56, totaling 42 days of feed efficiency trial.



	Pen 1	Pen 2	Pen 3	Pen 4	Pen 5
Trial 1	14 males BW1: 26.4±7.4 Age1: 217±14	18 males BW1: 30.2±1.5 Age1: 213±10	19 males BW1: 33.2±1.3 Age1: 222±8	19 males BW1: 36.1±2.8 Age1: 217±9	19 males BW1: 41.5±2.6 Age1: 223±4
Trial 2	16 males BW1: 50.6±4.1 Age1: 290±7	19 males BW1: 43.8±2.5 Age1: 285±9	19 males BW1: 38.8±5.2 Age1: 284±11	19 females BW1: 40.6±2.4 Age1: 289±5	20 females BW1: 34.4±2.2 Age1: 289±6
Trial 3	21 females BW1: 42.0±2.8 Age1: 339±11	21 females BW1: 37.5±2.0 Age1: 338±11	21 females BW1: 35.3±1.3 Age1: 340±10	21 females BW1: 33.5±2.0 Age1: 340±11	20 females BW1: 31.0±2.3 Age1: 339±8

Fig. 2. There were three food efficiency tests, and in each test the animals were allocated into five pens, divided considering the sex, type of birth and sire of the sheep, and body weight.

Data was continuously registered and transferred to the central computer and Intergado web software data center. To ensure the correct functioning of the equipment daily systematic calibration and on-site and online check were carried out.

2.3. Residual feed intake estimates

Two models were used to calculate residual feed intake (RFI). Using a similar methodology as proposed by Koch et al. (1963), average FI and ADG estimates were used for linear regressions of Model 1:

$$Y = \mu + P \times T + \mathrm{BW}^{0.75} + \mathrm{ADG} + e \qquad (1)$$

where Y = observed individual daily average feed intake (total feed intake per day) expressed in dry matter (fresh matter intake × proportion of dry matter – DMI, 53.73%); μ = is an all animals constant referred to average daily feed intake; $P \times T$ = is composed for pen per trial (15 levels; fixed effect); $\mathrm{BW}^{0.75}$ = is the metabolic body weight (MBW) (mid-test body weight elevated to 0.75 as covariable); ADG = is the average daily body-weight gain (g/day, covariable); and e = the residual error as

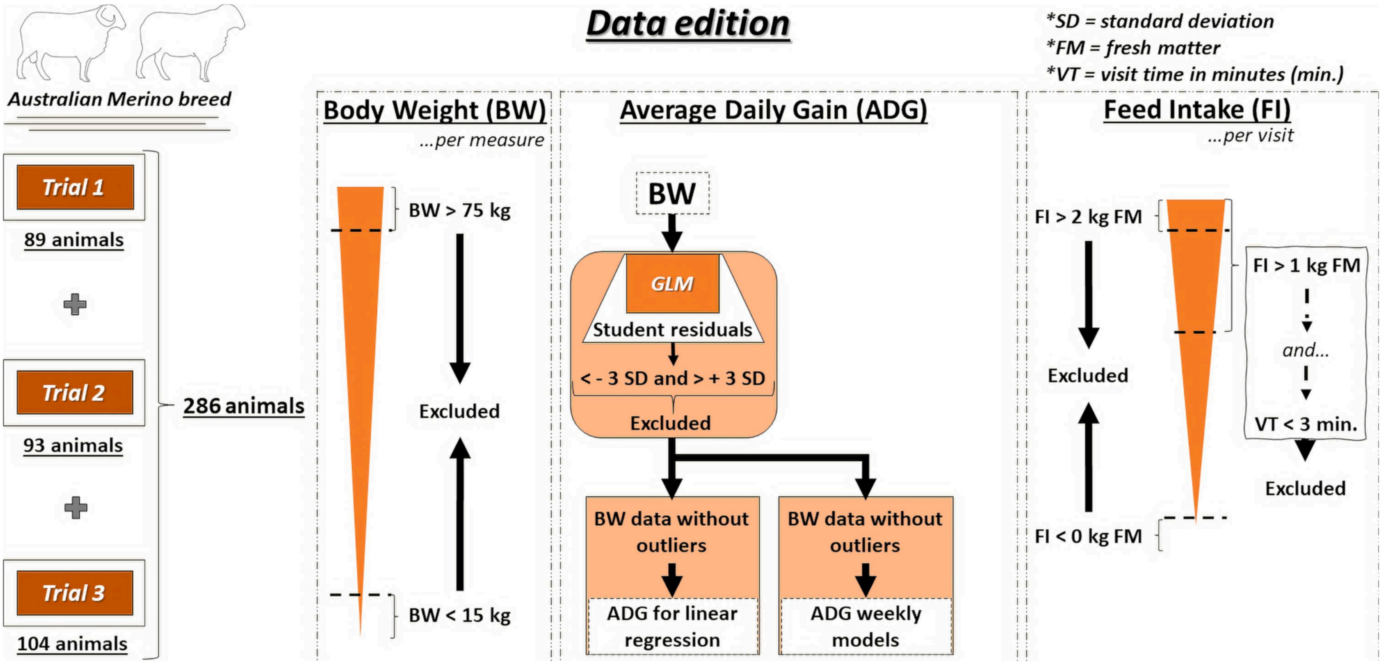


Fig. 3. Body weights less than 15 kg or greater than 75 kg per visit were excluded, judging that these weights are biologically improbable. Body weights that presented Student residuals ± 3 SD were also excluded and the remainder were used to calculate the average daily gains by linear and weekly models. Feed intake per visit with values greater than 2 kg or lower than 0 kg, as it were considered biologically improbable, they were excluded. Consumptions greater than 1 kg with a duration of less than 3 min were also excluded.

RFI (difference between the observed and expected DMI).

For Model 2, the average FI and ADG estimations by week were used:

$$Y_{rep} = \mu + \mathrm{P} \times \mathrm{T} + \mathrm{PER} + \mathrm{BW}^{0.75}{}_{rep} + \mathrm{ADG}_{rep} + e \qquad (2)$$

where Y_{rep} = observed week average individual daily feed intake (total feed intake per day) expressed in dry matter (fresh matter intake × proportion of dry matter – DMI, 53.73%); μ = is an all animals constant referred to average weekly feed intake; $P \times T$ = is composed for pen per trial (15 levels; fixed effect); PER = is the week as covariable; $\mathrm{BW}^{0.75}{}_{rep}$ = is the MBW (mid-week body weight elevated to 0.75 as covariable); ADG_{rep} = is the daily body-weight gain by week (g/day, covariable); and e = the residual error as RFI (difference between the observed and expected DMI).

2.4. Statistical analysis

The average and variance of daily BW and FI over the days in the three trials were examined using the R Package 'ggplot2' of software R version 4.0.1 (Wickham et al., 2020). To estimate RFI in Model 1, a general linear model (PROC GLM) was used, while to estimate Model 2, the PROC MIXED was performed in SAS program. The R-squares were plotted with radarchart function, using the R Package 'fmsb' (Nakazawa, 2019).

The dominance analysis method was used to compare the relative importance of predictors (covariables) in multiple regression model that compose the RFI models, using the R Package 'dominanceanalysis' (Navarrete and Soares, 2020), the results were plotted using the R Package 'ggplot2' (Wickham et al., 2020).

The FI, ADG and the output of RFI models were submitted of Pearson and Spearman correlation analysis, using the R Package 'corrplot' of software R version 3.5.3 (Wei and Simko, 2017).

3. Results

The average FI range for all RFI models was 1.25 to 1.33 kg dry matter basis (kg DM day^{-1}) and the coefficient of variation (CV) ranged from 17.75% to 19.13%. The ADG ranged from 0.133 to 0.186 kg per day (kg day^{-1}), with a CV from 33.50% to 54.07%. For MBW the values ranged from 15.37 to 16.71 kg, and CV from 11.50% to 11.88%.

On Fig. 4A and B a BW increase trend throughout the test period and different variabilities can be observed. In Fig. 4A, BW per day in trials 1 and 2 had a linear increase, while trial 3 had several BW falls, mostly after day 22, with a new increasing the after 37th day. The variances for BW, as shown in Fig. 4B, show the largest values were observed in trial 2 followed by trial 1. In these trials the variance increased, with an increment of 50.2% and 41.4%, respectively, for trials 2 and 1. However, trial 3 kept almost a constant variance throughout the test, with the peak on the 22nd day. The variance increased by just 21% between day one through day 42 in this trial. The standard errors relative per day per trial on average were, respectively, 0.15%, 0.15%, and 0.10% for trials 1, 2, and 3.

The FI behavior was not constant, with a positive tendency, as shown in Fig. 4C and D. In Fig. 4C the minimum intake point on trial 1 was on the 11th day with dry matter intake decrease of 10.9% compared with the start of the test. Moreover, on the day 22, the decrease was larger in the order of 21.2% compared with the beginning of the feed intake trial. The global increment of intake along the test period was 0.020 kg (+1.8%). In trial 2, which had better constancy in increasing intake along the test, presenting two discrete falls of intakes, one in the seventh and other on the ninth day compared to the beginning of the period of evaluation, respectively, 4.8% and 8.6% (Fig. 4C). Nonetheless, the intake increase over the entire period was 0.236 kg (+19.4%).

Four fall points were noted in trial 3, the first point was the fourth day represented a decrease compared with the first day of 2.5%. The second and greater decrease in FI was on the 12th day that represented 13.5% less dry matter consumed. The third and fourth fall points were on days 16 and 29 with a reduction in the order of 1.4% and 1.2%, respectively (Fig. 4C). Like the others, the trial 3 also presented an increase of intake up the test period of 0.175 kg (+16.3%).

As presented in Fig. 4D, the variances for FI show the largest values in trial 2. In this trial the variance behavior presented a large increase of the values, with an increment of 118.4%. In this trial, there were three

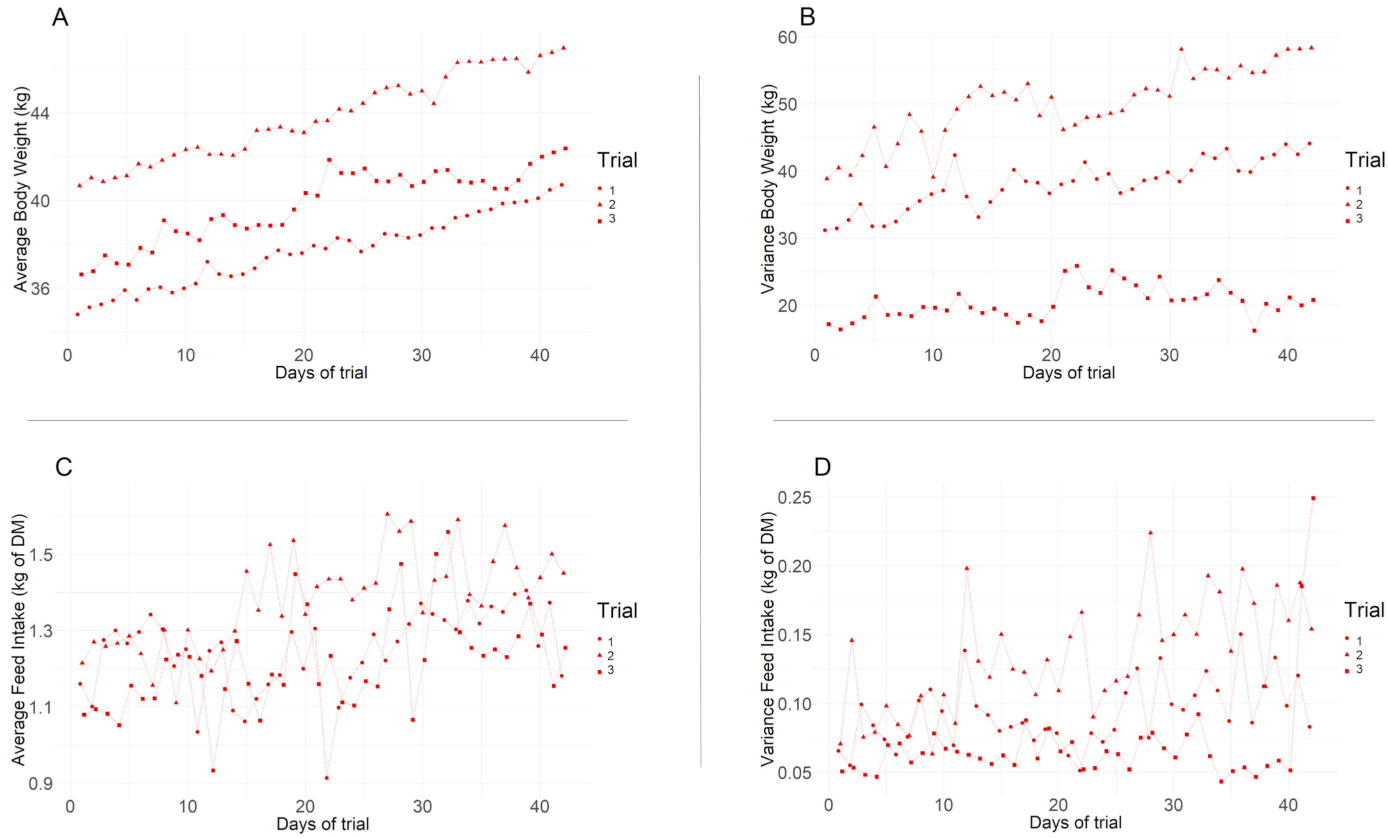


Fig. 4. Average and variance of the body weight and feed intake per day in the trials.

peak points, in days 2, 12 and 28 with an average increment of 168.4%. On the other hand, trial 1 had an increase between the first day and the 42nd of 26.5%. Despite a small total variation increase, the trial 1 had some peaks in the 13th, 29th and 36th days. The trial 3 kept almost constant the variance until 40th day, with a great increase in the day 41 following an increase in the 42nd day. The variance until day 40 increased by just 1.7% and an extreme increase of 393.5% between day one through day 42. The standard error relative per day per trial on average were, respectively, 0.22%, 0.24%, and 0.20% for trials 1, 2, and 3 (data not shown).

The Pearson and Spearman correlations for the models with a length of 42 days presented values from 0.89 to 0.87, respectively, for the ADG estimate for linear regression and ADG weekly (Fig. 5A and B).

In the ADG estimate by the linear model, the Pearson and Spearman correlations between the model of 42 days with the models of 35, 28, and 21 days were 0.95 and 0.94, 0.77 and 0.75, and 0.67 and 0.69, respectively. For the weekly ADG model approach the Pearson and Spearman correlations were from 0.96 to 0.95, 0.83 and 0.81, and 0.87 and 0.88, for the 42-day trial, considering 35, 28, and 21 days length models, respectively.

The FI correlations, both Pearson as Spearman presented values >0.93 not only between different length tests for linear and weekly models but also between linear and weekly models for any given length test (Fig. 5C and D).

The determinations coefficients (R-square) for the RFI models presented values ranging from 0.610 to 0.753, being the lowest value for the Model 2 (weekly FI and ADG) with 21 days on trial and the greatest value for the Model 1 (linear FI and ADG) with 35 days (Fig. 6). Linear models (model 1) with 42, 28 and 21 days presented R-square from 0.752, 0.734 and 0.693, respectively. For the weekly models (model 2), the values of R-square found were 0.634, 0.636 and 0.629 for 42, 35 and 28 days.

The greater contribution in the dominance analysis for all models was the MBW, ranging from 0.29 to 0.33 (Fig. 7). The models that MBW had an importance smaller than 0.30 were the Model 1 with 42 days and the Model 2 with 21 days, presented an R-square of 0.29 for both. Sequentially, the Model 1 with 35, 28 and 21 days, presented the R-square of 0.30, 0.31 and 0.31, respectively. For the Model 2 with 42, 35 and 28 days the R-squares, respectively, were 0.33, 0.33 and 0.31.

The ADG contribution ranged from 0.04 (Models 2 with 42 days) to 0.19 (Model 1 with 42 days). The other Models 1 presented, respectively, an ADG contribution from 0.18, 0.13, and 0.12, for 35, 28, and 21 days. The other Models 2 with 35, 28, and 21 days on trial presented R-square for ADG from 0.05, 0.08 and 0.1, respectively (Fig. 7).

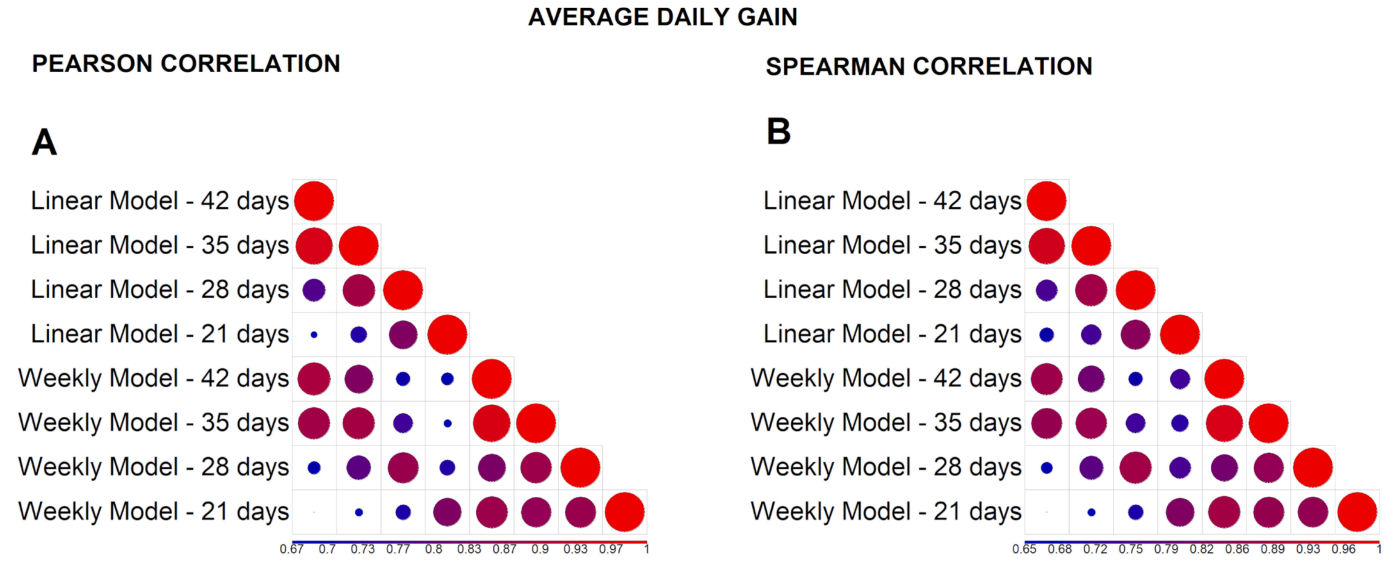
The fixed effect Pen per trial (Pen × Trial) in all models presented a contribution greater than 0.19, and the covariable week for Models 2, presented a contribution smaller than 0.05 (data not showed).

The RFI models with 42 days of trials presented a Pearson correlation of 0.93 between the Model 1 and Model 2 (Fig. 8A). While the Spearman correlation value between Model 1 and Model 2 was 0.92 (Fig. 8B).

In Model 1, comparing the 42 days with the 35, 28, and 21 days, the Pearson and Spearman correlations, respectively, were 0.98 and 0.98, 0.94 and 0.94, and 0.88 and 0.90 (Fig. 8A and B). Finally, in Model 2, the Pearson and Spearman correlations presented values from 0.98, 0.95, and 0.88, respectively, between 42 days with 35, 28, and 21 days (Fig. 8A and B).

4. Discussion

Decreasing the trials period in one week or more would allow test more animals with the same resources without accuracy losses in the phenotypic measurements. The use of methods for weight gain estimation with a linear model or calculations by week, the use of BWs measures, as well as considering the FI as a repeated measure, would allow to reduce the test time without loss of precision.



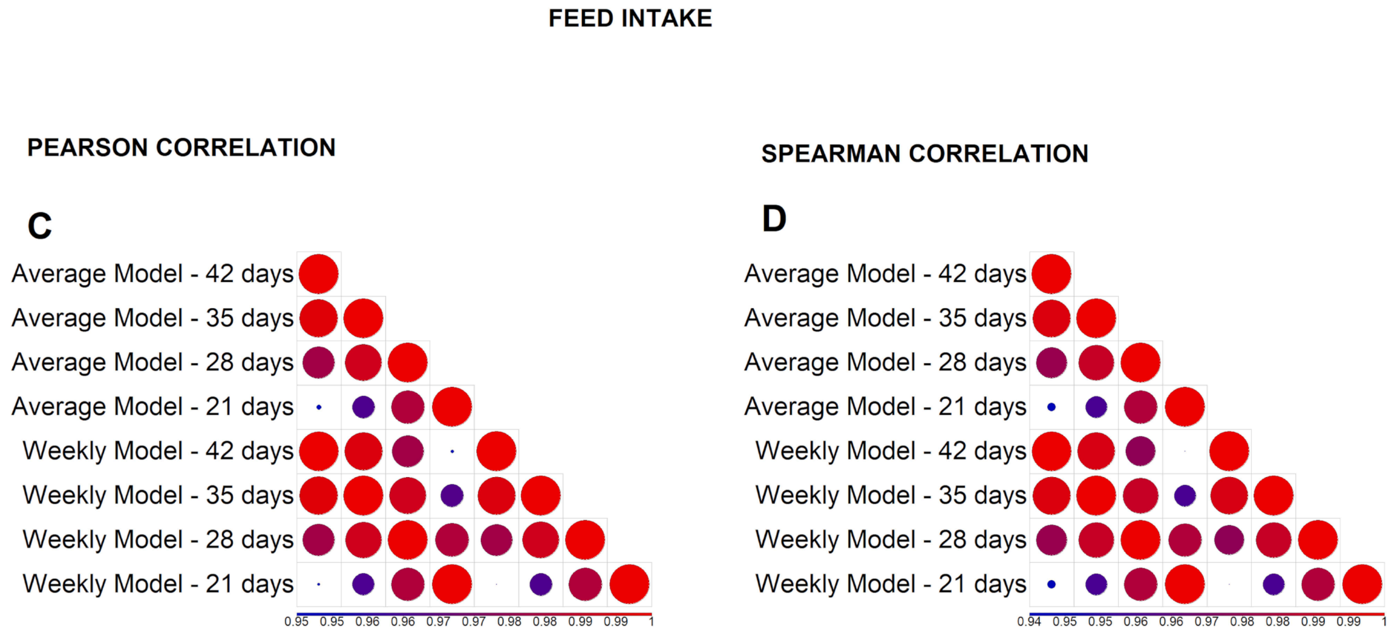


Fig. 5. Pearson and Spearman correlation among the ADG estimates (A and B) and FI measurements (C and D), for different models. The bigger and red the circles the closer to 1 are the correlations and the smaller and blue the circles, the closer to lower values are the correlations. *p-value $<$ 0.05 for all Pearson and Spearman correlations. **Linear Model – 42 days – ADG linear model with 42 days on trial; Linear Model - 32 days – ADG linear model with 35 days on trial; Linear model - 28 days – ADG linear model with 28 days on trial; Linear Model - 21 days – ADG linear model with 21 days on trial; Weekly Model - 42 days – ADG weekly model with 42 days on trial; Weekly Model - 35 days – ADG weekly model with 35 days on trial; Weekly Model - 28 days – ADG weekly model with 28 days on trial; Weekly Model - 21 days – ADG weekly model with 21 days on trial; Average Model - 42 days – Average FI model of the 42 days on trial; Average Model - 35 days – Average FI model of the 35 days on trial; Average Model - 28 days – Average FI model of the 28 days on trial; Average Model - 21 days – Average FI model of the 21 days on trial; Weekly Model - 42 days – Average FI model per week into 42 days of trial; Weekly Model - 35 days – Average FI model per week into 35 days of trial; Weekly Model - 28 days – Average FI model per week into 28 days of trial; and Weekly Model - 21 days – Average FI model per week into 21 days of trial. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

4.1. *Average daily gain*

A BW evolution along the trials is noted in the Fig. 4A and B, characterized by a linear increase of BW, along with a variation not so linear. This can be explained by the fluctuations across all animals occurred between weightings, even on consecutive days. Fluctuations on BW are due to possible variations in gut fill, hour of the day, water consumption, FI or rain. However, those fluctuations were corrected when estimating the ADGs by linear regression. The studies of Johnson et al. (2015a, 2016, 2017) presented ADG ranging from 0.231 to 0.332 kg live weight per day for 9 months-old ewe lambs from maternal breeds (synthetic breed as Coopworth and different crossbreeding by industry sires of different breeds). Thus, our results have not achieved the values described by these studies. This fact may be due the difference in the evaluate animals age, the adult BW inherent the animals' racial composition in the revised studies, and productive fitness of the breeds,

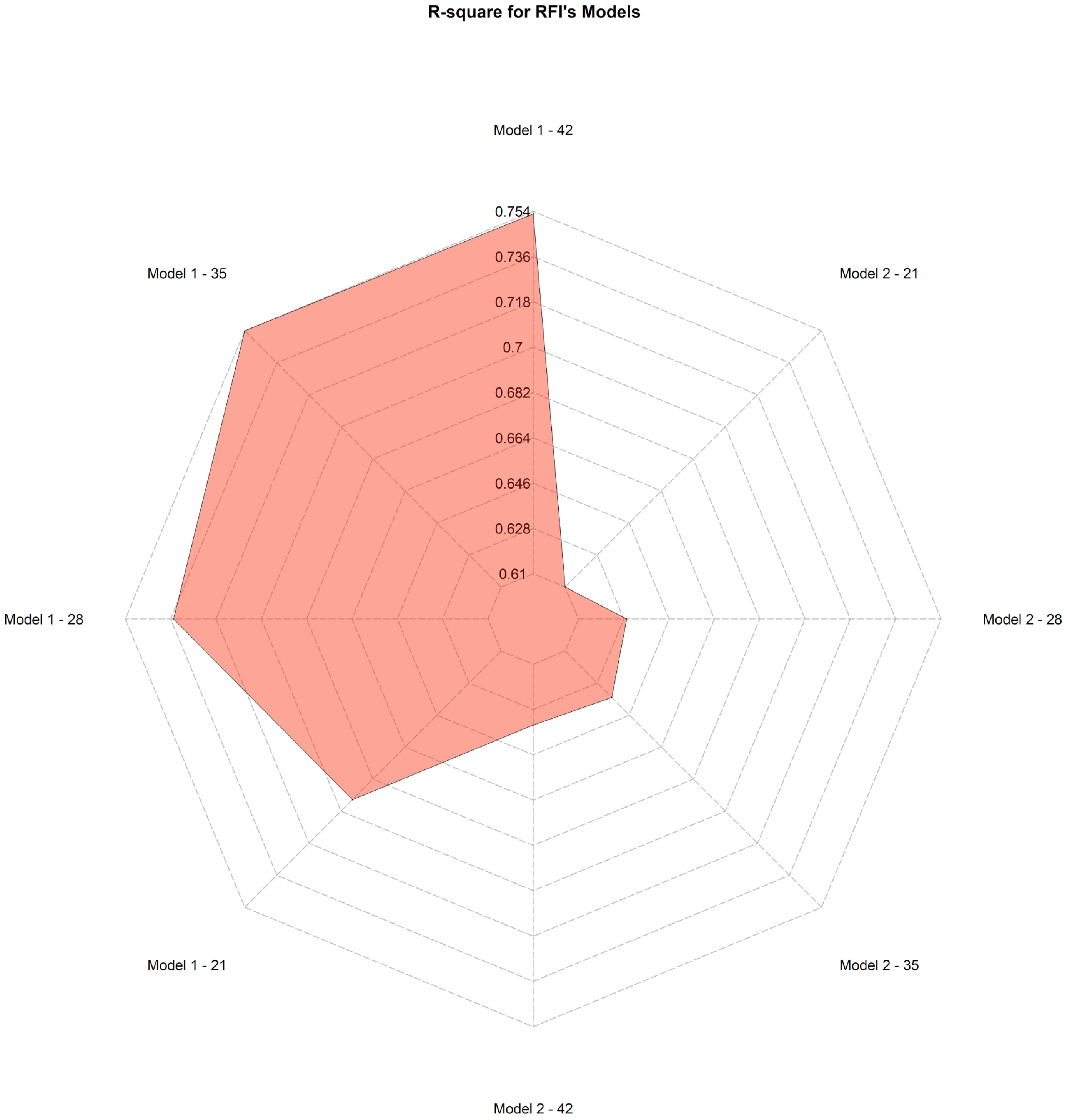


Fig. 6. R-square for different RFI models. *Model 1 - 42 – linear model with 42 days on trial; Model 1 - 35 – linear model with 35 days on trial; Model 1 - 28 – linear model with 28 days on trial; Model 1 - 21 – linear model with 21 days on trial; Model 2 - 42 – weekly model with 42 days on trial; Model 2 - 35 – weekly model with 35 days on trial; Model 2 - 28 – Weekly model with 28 days on trial; and Model 2 - 21 – weekly model with 21 days on trial.

compared at Australian Merino sheep raised in Uruguay.

The ADG correlations showed that there is a different classification in the different complete models, however, to maintain accuracy, the linear and weekly models with 35 days presented good Pearson and Spearman correlation (> 0.90) with the respective linear and weekly models with 42 days. According to Waldron et al. (1990), if the duration of an ADG performance test is too short, animals may not be properly ranked for genetic merit, resulting in an extremely low relationship between the sire's performance and the performance of its progeny Waldron et al. (1990). suggest that test performance measured on 63 days has an insufficient period as an indicator of breeding value for growth. Results from the single-trait analyses clearly imply that variances for ADG can be influenced by the duration of the adjustment period and of the performance test (Snowder and Van Vleck, 2002). The higher heritability for ADG was found in tests that used an adaptation period of two weeks, and the performance trial duration from eight weeks or longer. The results of Snowder and Van Vleck (2002) point out for the largest amount of genetic variation in ADG must be accounted

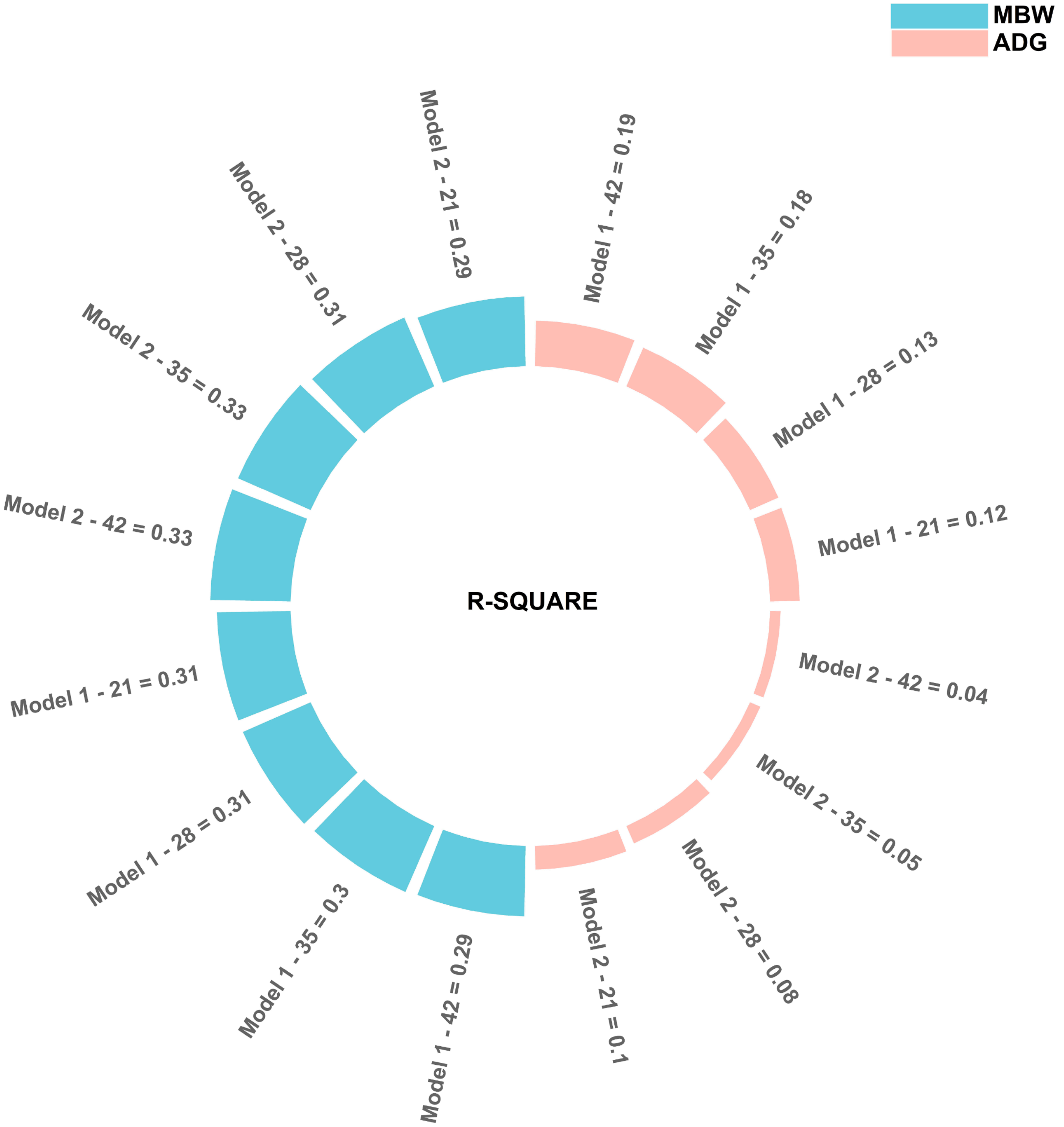


Fig. 7. Average contribution (R-square) of the covariables of the RFI models. *ADG – Covariable of average daily gain and MBW – covariable of metabolic body Weight. ** Model 1 - 42 – RFI linear model with 42 days on trial; Model 1 - 32 – RFI linear model with 35 days on trial; Model 1 - 28 – RFI linear model with 28 days on trial; Model 1 - 21 – RFI linear model with 21 days on trial; Model 2 - 42 – RFI weekly model with 42 days on trial; Model 2 - 35 – RFI weekly model with 35 days on trial; Model 2 - 28 – RFI weekly model with 28 days on trial; and Model 2 - 21 – RFI weekly model with 21 days on trial.

using a test period of 42 to 98 days for accurately identifying genetic differences between animals for ADG Archer et al. (1997). obtained optimal periods different of records for beef cattle with 70 days of evaluation. Is important highlight that these studies did not collect daily BW, this practice provides the possibility of decreasing of the days of ADG without loss accuracy in the growth test as shown in the Fig. 5A and B. Thanks to the fact that in our study the BW was measured daily, it was possible to adjust all daily measurements along of the tests to a straight line with a greater or lesser inclination, which allowed an ADG estimation that reflects the real profile of the BW progression over the days.

4.2. Feed intake

As shown in Fig. 4C and D, the FI is extremely variable, this could be

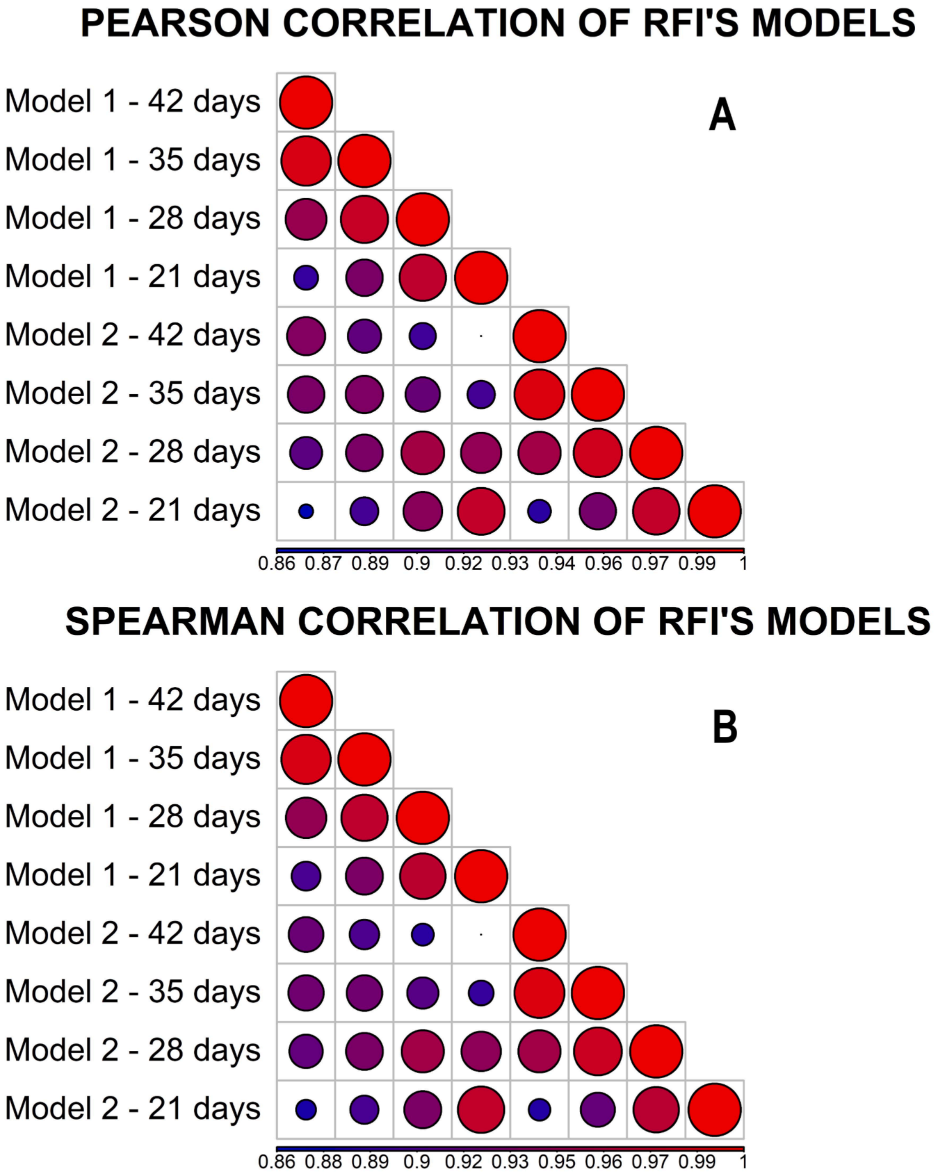


Fig. 8. Pearson (A) and Spearman (B) correlation among the different RFI models. The bigger and red the circles the closer to 1 are the correlations and the smaller and blue the circles, the closer to lower values are the correlations. *p-value < 0.05 for all Pearson and Spearman correlations. ** Model 1 - 42 days – RFI linear model with 42 days on trial; Model 1 - 32 days – RFI linear model with 35 days on trial; Model 1 - 28 days – RFI linear model with 28 days on trial; Model 1 - 21 days – RFI linear model with 21 days on trial; Model 2 - 42 days – RFI weekly model with 42 days on trial; Model 2 - 35 days – RFI weekly model with 35 days on trial; Model 2 - 28 days – RFI weekly model with 28 days on trial; and Model 2 – 21 days – RFI weekly model with 21 days on trial. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

explained due to several mechanisms that act in the regulation of consumption Allen (2014). describes that the response of feeding behavior to the diet is influenced by the energy supply in blood which is affected by physiological state, such as differences in liver gluconeogenesis, mobilization, extrahepatic tissue energy uptake, tissue secretion and sensitivity to hormones and cytokines. This can affect satiety and hunger over the span of minutes and hours and can have long-term effects on FI and energy balance, explaining the greater variability in FI, as shown in Fig. 4D. As the animals in the present study were evaluated outdoors, in addition to internal factors, the effects of the environment such as rain, heat, cold and wind could also influence the FI regulation. Therefore, in the present study the total precipitation, daily average temperature, and average thermal amplitude, not do seem to be challenging enough to influence average FI (data not considered directly in the model).

As there are several factors that affect FI and considering the difference in diets, the comparison of absolute FI values found in this study with other works is not indicated. This fact is very important to highlight since several authors found an interaction between feed efficiency and diet type (Cammack et al., 2014; Carberry et al., 2012; Coyle et al., 2016; Durunna et al., 2011; Ellison et al., 2017; François et al., 2006; Toral et al., 2019). When the diet is based on roughage, the mechanism that controls the intake probably is similar to the mentioned by Cantalapiedra-Hijar et al. (2018). These authors suggest that when a pasture is offered, ruminal distension is more likely to dominate FI control than tissue energy detection. In our study, with an NDF of 36,1%, the intake control was dictated by rumen filling, in which according to Dado and Allen (1995) the forage offered with an NDF greater than 35% would already limit feed intake.

As observed in Fig. 4C and D, the FI over the test period presents a non-linear behavior and high variability. The FI coefficient of variation (CV) is a good descriptive variable Basarab et al. (2013). describe that CV for FI in beef cattle is commonly found in values ranging from 11% to 20%, and this is due to the fact that intake is a reflection of natural daily between-animal variation between animals. This is due that FI is a function of meal size and frequency with meal size determined for the rate of eating and meal length and meal frequency determined for the length of time between meals (Allen, 2014). In our study the CV of FI ranged from 17.75% to 19.13%, similarly to the described by Basarab et al. (2013), however higher than results of 7.3%, 13%, 17.1% and 13% reported by Ermias et al. (2002); François et al. (2002); Cammack et al. (2005) and Tortereau et al. (2019), respectively.

In sheep studies, the FI varied from 0.838 at 3.94 kg of dry matter per day, a large variation among studies. In Ermias et al. (2002) study, the average daily total dry matter intake was of 0.84 kg. However, François et al. (2002); Cammack et al. (2005) and Redden et al. (2011) found FI values of 1.79, 1.69 and 1.77 kg, respectively. The FI values found by Cockrum et al. (2013) ranged from 2.85 to 3.94 kg, Johnson et al. (2015a) found feed intake ranges from 2.7 to 3.3 kg. Feed intakes ranging from 1.09 to 1.33 kg were published by Zhang et al. (2017). In the study of Lima Montelli et al. (2019) FI from 1.25 to 1.44 kg were found Tortereau et al. (2019). found FI from 1.96 kg. Thus, the feed intakes from 1.25 to 1.32 kg found in our study on the different models and times of measurements, is within what is reported in the bibliography, which not was a limiting factor of animals' performance.

The very high Pearson and Spearman FI correlations for linear and weekly models 42-days with respective 35-, 28- and 21-days models showed that is possible to reduce the days on test without losing accuracy in animal's classification De Castilhos et al. (2011). describe that the variances for FI decreased by 0.18% from 28 to 56 days, increased 13.67% from 56 to 84 days, and increased by 11.22% from 84 to 112 days. This might be attributed to the increase of dry matter intake due to the increase in BW gain over the test period. As the variance for dry matter intake did not stabilize over the test period, Pearson and Spearman correlations were used to determine the optimum test period, presented values higher than 0.93 for these authors Archer et al. (1997). comparing different periods of records in beef cattle found that a 35 days was sufficient for feed intake records. Considering only the FI, the high Pearson and Spearman correlations could make it possible to safely reduce from one to three weeks of experimental period in our study. The increase in FI after 28 tends to decelerate (Fig. 4C), tending to maintain the proportion between animals that have a higher and lower FI, reflecting in correlations greater than 0.93.

4.3. *Metabolic body weight*

The values of MBW ranged from 15.67 to 16.14 kg, and CV from 11.63% to 11.75%, showing low variability Redden et al. (2011). found MBW ranging from 19.6 to 21.1 kg. Moreover, a MBW range from 12.97 to 13.18 kg were published by Zhang et al. (2017). In the study of Lima Montelli et al. (2019) the average MBW was 13.7 kg. Our MBW values do not match with the studies described above. Therefore, this could be explained by the fact that MBW is dependent on several factors such as age of dam, type of birth, weaning and standard/normal adult weight of the breed.

4.4. *Residual feed intake*

The R-square in the FI prediction model is a criterion used to indicate how suitable is the RFI model. In this sense, as showed in Fig. 6, our models were able to explain a portion of 61.0% to 75.3% (R-square from 0.61 to 0.753). According to the R-square, the best RFI model was the linear RFI model with 35 days on trial. Using a methodology similar to Model 1, Knott et al. (2008) found an R-square of 0.63 and 0.56 for rams at 6 and 13 months old, respectively. In the model composed for ADG and live weight in the mid-test, Knott et al. (2008) reached R-square equal to 0.74 and 0.60 for 6 and 13 months old rams, respectively. For animals tested in two subsequent ages, the R-square were 0.41 and 0.38 for ewes with 280 and 414 days old, respectively, (Redden et al., 2011) Cockrum et al. (2013). found coefficients of determination for several residual feed intake models estimates range 0.43 to 0.46. In the study of Johnson et al. (2015a), the model fitted with live weight, ADG, previous feed, and feeder in the current trial and the intake of the animals had an R-square of 0.79 Redden et al. (2014). found the R-square equal to 0.84 Johnson et al. (2016). found the coefficient of determination for the RFI model from 0.78 Johnson et al. (2017). present a R-square of the RFI model has been greater than 0.70. For Zhang et al. (2017) the R-square for the RFI model was 0.80. The RFI presented a coefficient of determination of 0.82 in the study of Lima Montelli et al. (2019). For RFI model of Tortereau et al. (2019) the R-square values ranging from 0.63 to 0.84. Our results fall within a wide range of R-square, where the smallest found in the bibliography was 0.38 and the largest was 0.84. Therefore, is a consensus in those several studies reviewed that of goodness of fit values of R-square do not be smaller than 0.70. Thus, the Model 1 with 42, 35 and 28 days of our study are into this range and represents that this model was able to predict FI with good accuracy. That would mean that the covariates of the model would be good predictors of FI (Fig. 7 and the next discussion section).

The Fig. 8 confirms our results, showing the Pearson and Spearman correlations ($P<0.05$) of all RFI models, confirming with values greater than 0.98 of Pearson and Spearman correlations ($P<0.001$) that the RFI models (Models 1 and 2) with 35 days is the best reduced model. The use of this model, in practice, not will cause animal significant reranked in the FI, ADG, and neither on RFI classification.

The validation of the recommendation for a decrease of the days on trial, it will only be conclusive when beyond of phenotypic correlation, the genetic correlations are known (Goonewardene et al., 2004). If the testing time can be shortened while maintaining the same degree of accuracy, by correctly classifying animals into their respective (positive and negative) feed efficiency categories with minimal rank changes, then on-test feeding costs may be reduced Goonewardene et al. (2004). found Pearson correlations phenotypic in the comparisons of 0–84 days with 0–105 days ranging from 0.85 to 0.93 Knott et al. (2008). describe that highly significant rank correlation values between each of the RFI models, are of key importance as they indicate that animals maintain the same relative rankings in each model at each time of measurement. However, the phenotypic correlations among the models of the Knott et al. (2008) study, ranged from 0.43 to 0.76. The correlations found for Cockrum et al. (2013), between weekly RFI estimates and between weekly RFI rankings were performed to determine the applicability of RFI estimates throughout the testing period, ranged from 0.30 to 0.82 for Pearson correlations and 0.28 to 0.80 for Spearman correlations. With a basis on these studies, our work presented safe results for deciding to decrease the time on trial in one week maintaining the rank of the animals satisfactorily.

4.5. *Average contribution*

For a better understanding of the models, an analysis of dominance as described for Navarrete and Soares (2020) was proposed. The importance of MBW was observed on all models (Fig. 7). The portion of the contribution of ADG and MBW of the RFI Models 1 in 42 and 35 days on our study was lower compared with the work of Knott et al. (2008). The models evaluated for Knott et al. (2008) clearly indicate that the MBW and ADG accounted a substantial proportion of the variation in FI in a group of animals at both 6 months old (R-square varied from 0.48 to 0.73), and at 13 months old (R-square varied from 0.48 to 0.49). In our study the average contribution from MBW and ADG were of the 0.29–0.31 and 0.12–0.19, respectively, for the Model 1, and 0.29 – 0.33 and 0.04 – 0.10, respectively, for the Model 2. This means that the FI variation among the animals is explained by up to 31% (Model 1) and 33% (Model 2) for the MBW. That is represent the percentage of cases in that the FI increase, or decrease is due to one unit increased or decreased of the MBW. This show that it is possible to find animals with high MBW and low FI and vice versa. The ADG average contribution is lower, by up to 0.19 (Model 1) and 0.10 (Model 2). Using the same logic and comparing with MBW, is possible to find more animals with high ADG and low FI and vice versa.

4.6. *Shorter duration trials*

We found only the works of Redden et al. (2011); Macleay et al. (2016) and Paganoni et al. (2017) where less than 42 days were used in the trial period. Experiment 1 in the study of Redden et al. (2011), worked with a period of 38 days of evaluation, however, the original trial length is 49 days, because the last 11 days not was recorded due to a computer system failure. Already in the Macleay et al. (2016) study, the feed intake in sheep was measured until 35 days. In Paganoni et al. (2017) the RFI was estimated with a trial of 35 days. In others studies the evaluation period was from 42 days in Leymaster et al. (2002); Cammack et al. (2005); Johnson et al. (2015b, 2017, 2016), and in the second approach of Tortereau et al. (2019). With 49 days can mention experiment 1 of Knott et al. (2008), studies of Cammack et al. (2014); Redden et al. (2014), and Ellison et al. (2017). With 50 days, the study of Zhang et al. (2017), 56 days in the work of Cameron (1988); François et al. (2007, 2006, 2002); Lima Montelli et al. (2019) and in the first approach of Tortereau et al. (2019). Evaluations periods with more than 62 days, we found in the Waldron et al. (1990), in experiment 2 of Knott et al. (2008); Cockrum et al. (2013); Paula et al. (2013), and in Carneiro et al. (2019). Those evidence, together with correlations presented in Fig. 8, reinforce our arguments that it is possible to shorten the tests of feed efficiency, these being promising findings. However, it would be suitable to evaluate the genetic correlations of the different traits with different test periods and a greater number of data to have a validation of the proposal.

5. Conclusion

Reducing seven days of testing would provide great impacts. In a year where usually six batches would be tested, an additional batch could be included at the same cost. If resources saved by shortening test duration are used to test related animals and the data from relatives are used in genetic evaluations, the loss of accuracy of using a shorter test duration will be partly compensated by the extra information obtained by measuring an additional related individual. In this way, data collection could be accelerated, and selection intensity increased.

Authors' statement

The corrections proposed by the reviewer were all considered and corrected/answered. However, the article underwent other minor revisions in order to improve the quality of writing so that the reviewer can find a better fluidity in its reading.

Declaration of Competing Interest

The authors declare no conflict of interest.

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References

Allen, M.S., 2014. Drives and limits to feed intake in ruminants. Anim. Prod. Sci. 54, 1513–1524. https://doi.org/10.1071/AN14478.

Archer, J.A., Arthur, P.F., Herd, R.M., Parnell, P.F., Pitchford, W.S., 1997. Optimum postweaning test for measurement of growth rate, feed intake, and feed efficiency in British breed cattle. J. Anim. Sci. 75, 2024–2032. https://doi.org/10.2527/1997.7582024x.

Basarab, J.A., Beauchemin, K.A., Baron, V.S., Ominski, K.H., Guan, L.L., Miller, S.P., Crowley, J.J., 2013. Reducing GHG emissions through genetic improvement for feed efficiency: effects on economically important traits and enteric methane production. Animal 7 (Suppl 2), 303–315. https://doi.org/10.1017/S1751731113000888.

Cameron, N.D., 1988. Genetic relationships between growth and food intake in performance tested ram lambs: an investigation of variance component estimation procedures. J. Anim. Breed. Genet. 105, 431–440. https://doi.org/10.1111/j.1439-0388.1988.tb00316.x.

Cammack, K.M., Ellison, M.J., Conant, G., Lamberson, W.R., Austin, K.J., 2014. Rumen microbial taxa and by-products associated with feed efficiency in sheep. In: Proceedings 14th World Congress of Genetics Applied to Livestock Production, pp. 14–16.

Cammack, K.M., Leymaster, K.A., Jenkins, T.G., Nielsen, M.K., 2005. Estimates of genetic parameters for feed intake, feeding behavior, and daily gain in composite ram lambs. J. Anim. Sci. 83, 777–785. https://doi.org/10.2527/2005.834777x.

Cantalapiedra-Hijar, G., Abo-Ismail, M., Carstens, G.E., Guan, L.L., Hegarty, R., Kenny, D. A., Mcgee, M., Plastow, G., Relling, A., Ortigues-Marty, I., 2018. Review: biological determinants of between-animal variation in feed efficiency of growing beef cattle. Animal. https://doi.org/10.1017/S1751731118001489.

Carberry, C.A., Kenny, D.A., Han, S., McCabe, M.S., Waters, S.M., 2012. Effect of phenotypic residual feed intake and dietary forage content on the rumen microbial community of beef cattle. Appl. Environ. Microbiol. 78, 4949–4958. https://doi.org/10.1128/AEM.07759-11.

Carneiro, M.M.Y., Morais, M.da G., Souza, A.R.D.L., Fernandes, H.J., Feijó, G.L.D., Bonin, M.de N., Franco, G.L., Rocha, R.F.A.T., 2019. Residual intake and gain for the evaluation of performance, non-carcass components, and carcass characteristics of confined crossbred Texel lambs. Rev. Bras. Zootec. 48 https://doi.org/10.1590/rbz4820180206.

Cockrum, R.R., Stobart, R.H., Lake, S.L., Cammack, K.M., 2013. Phenotypic variation in residual feed intake and performance traits in rams. Small Rumin. Res. 113, 313–322. https://doi.org/10.1016/j.smallrumres.2013.05.001.

Coyle, S., Fitzsimons, C., Kenny, D.A., Kelly, A.K., McGee, M., 2016. Repeatability of feed efficiency in steers offered a high-concentrate diet. J. Anim. Sci. 94, 719. https://doi.org/10.2527/jam2016-1482.

Dado, R.G., Allen, M.S., 1995. Intake limitations, feeding behavior, and rumen function of cows challenged with rumen fill from dietary fiber or inert bulk. J. Dairy Sci. 78, 118–133. https://doi.org/10.3168/jds.S0022-0302(95)76622-X.

de Castilhos, A.M., Branco, R.H., Razook, A.G., Bonilha, S.F.M., Mercadante, M.E.Z., de Figueiredo, L.A., 2011. Duração do período de avaliação pós-desmame para medidas de desempenho, consumo e eficiência alimentar em bovinos da raça. Nelore. Rev. Bras. Zootec. 40, 301–307.

Durunna, O.N., Mujibi, F.D.N., Goonewardene, L., Okine, E.K., Basarab, J.A., Wang, Z., Moore, S.S., 2011. Feed efficiency differences and reranking in beef steers fed grower and finisher diets. J. Anim. Sci. 89, 158–167. https://doi.org/10.2527/jas.2009-2514.

Ellison, M.J., Conant, G.C., Lamberson, W.R., Cockrum, R.R., Austin, K.J., Rule, D.C., Cammack, K.M., 2017. Diet and feed efficiency status affect rumen microbial profiles of sheep. Small Rumin. Res. 156, 12–19. https://doi.org/10.1016/j.smallrumres.2017.08.009.

Ermias, E., Yami, A., Rege, J.E.O., 2002. Genetic parameters of feed intake and digestive efficiency in tropical sheep. In: 7th World Congr. Genet. Appl. Livest. Prod., 7, pp. 19–23.

François, D., Bibé, B., Bouix, J., Brunel, J.C., Weisbecker, J.L., Ricard, E., 2002. Genetic parameters of feeding traits on meat sheep. In: 7th World Congr. Genet. Appl. Livest. Prod., 7, pp. 19–23.

François, D., Bouix, J., Brunel, J.C., Ricard, E., Marcon, D., Weisbecker, J.L., Bibé, B., 2006. Genetic parameters of feeding traits in INRA401 sheep estimated under two different diets. In: 8th World Congr. Genet. Appl. Livest. Prod., 8, pp. 13–18.

François, D., Brunel, J.C., Ricard, E., Weisbecker, J.L., Bouix, J., Bourdillon, Y., Bibé, B., 2007. Use in selection of the measurements of feed intake and feeding behaviour parameters in sheep. Opt. Méditer. 74 (A), 441–447.

Goonewardene, L.A., Okine, E., Wang, Z., Spaner, D., Mir, P.S., Mir, Z., Marx, T., 2004. Residual metabolizable energy intake and its association with diet and test duration. Can. J. Anim. Sci. 84, 291–295. https://doi.org/10.4141/A03-073.

Johnson, P., Miller, S., Knowler, K., 2015a. Towards a data set to investigate feed efficiency in New Zealand maternal sheep. Proc. Assoc. Adv. Anim. Breed. Genet. 21, 106–109.

Johnson, P., Miller, S., Knowler, K., Bryson, B., Dodds, K., 2015b. Modelling liveweight change to inform a residual feed intake model in sheep. Proc. N. Z. Soc. Anim. Prod. 75, 225–227.

Johnson, P.L., Miller, S.P., Knowler, K., 2016. Preliminary investigations into the trait of residual energy intake in sheep. N. Z. Soc. Anim. Prod. Proc. 76, 34–37. https://doi.org/10.1079/BJN19660078.

Johnson, P.L., Wing, J., Knowler, K., 2017. Relationship between measures of residual energy intake made on growing animals and adults. N. Z. Soc. Anim. Prod. Proc. 77, 85–87. https://doi.org/10.1079/BJN19660078.

Knott, S.A., Cummins, L.J., Dunshea, F.R., Leury, B.J., 2008. The use of different models for the estimation of residual feed intake (RFI) as a measure of feed efficiency in meat sheep ઙ 143, 242–255. https://doi.org/10.1016/j.anifeedsci.2007.05.013.

Koch, R.M., Swiger, L.A., Chambers, D., Gregory, K.E., 1963. Efficincy of feed use in beef cattle. J. Anim. Sci. 22, 486–494.

Leymaster, K., Cammack, K., Nielsen, M.K., Jenkins, T.G., 2002. Estimates of genetic parameters for daily gain, feed intake, and behavior traits in ram lambs of a composite population. In: 7th World Congr. Genet. Appl. Livest. Prod., pp. 1986–1989.

Lima Montelli, N.L.L., Almeida, A.K.de, Ribeiro, C.R.de F., Grobe, M.D., Abrantes, M.A. F., Lemos, G.S., Furusho Garcia, I.F., Pereira, I.G., 2019. Performance, feeding behavior and digestibility of nutrients in lambs with divergent efficiency traits. Small Rumin. Res. 180, 50–56. https://doi.org/10.1016/j.smallrumres.2019.07.016.

Macleay, C., Blumer, S., Hancock, S., Inglis, L., Paganoni, B., Rose, G., Thompson, A.N., 2016. Feed intake for sheep can be measured precisely in less than 35 days. In: Proc. Aust. Soc. Anim. Prod. Brief Comm..

Nakazawa, M., 2019. Functions for medical statistics book with some demographic data.

Navarrete, C.B., Soares, F.C., 2020. Dominance analysis - CRAN.

Paganoni, B., Rose, G., Macleay, C., Jones, C., Brown, D.J., Kearney, G., Ferguson, M., Thompson, A.N., 2017. More feed efficient sheep produce less methane and carbon dioxide when eating high-quality pellets. J. Anim. Sci. 95, 3839. https://doi.org/10.2527/jas2017.1499.

Paula, E.F.E., Monteiro, A.L.G., Souza, D.F., Prado, O.R., Nomura, T.M., Stivari, T.S.S., Silva, C.J.A., Santana, M.H.A., 2013. Consumo alimentar residual e sua relação com medidas de desempenho e eficiência e características in vivo da carcaça de cordeiros. Arq. Bras. Med. Vet. e Zootec. 65, 566–572. https://doi.org/10.1590/S0102-09352013000200037.

Redden, R.R., Surber, L.M.M., Grove, A.V., Kott, R.W., 2014. Effects of residual feed intake classification and method of alfalfa processing on ewe intake and growth. J. Anim. Sci. 92, 830–835. https://doi.org/10.2527/jas.2013-6768.

Redden, R.R., Surber, L.M.M., Roeder, B.L., Nichols, B.M., Paterson, J.A., Kott, R.W., 2011. Residual feed efficiency established in a post-weaning growth test may not result in more efficient ewes on the range. Small Rumin. Res. 96, 155–159. https://doi.org/10.1016/j.smallrumres.2010.12.007.

Snowder, G.D., Van Vleck, L.D., 2002. Effect of duration of performance test on variance component estimates for lamb growth rate. J. Anim. Sci. 80, 2078–2084. https://doi.org/10.2527/2002.8082078x.

Toral, P., Belenguer, Á., Hervás, G., Fernández-Díez, C., Yáñez Ruiz, D., Frutos, P., 2019. Residual feed intake and rumen bacterial diversity in lactating sheep: a preliminary study of their potential link. In: 13o International Syposium on Ruminant Physiology, p. 191.

Tortereau, F., Marie-Etancelin, C., Weisbecker, J.L., Marcon, D., Bouvier, F., Moreno-Romieux, C., François, D., 2019. Genetic parameters for feed efficiency in Romane rams and responses to single-generation selection. Animal. https://doi.org/10.1017/S1751731119002544.

Waldron, D.F., Thomas, D.L., Stookey, J.M., Nash, T.G., Keith, F.K., Fernando, R.L., 1990. Central ram tests in the midwestern United States: III. Relationship between sire's central test performance and progeny performance. J. Anim. Sci. 68, 45–53. https://doi.org/10.1093/ansci/68.1.45.

Wei, T., Simko, V., 2017. Visualization of a correlation matrix - CRAN.

Wickham, H., Chang, W., Henry, L., Pedersen, T.L., Takahashi, K., Wilke, C., Woo, K., Yutani, H., Dunnington, D., 2020. Create elegant data visualisations using the grammar of graphics description - CRAN.

Zetouni, L., Henryon, M., Kargo, M., Lassen, J., 2017. Direct multitrait selection realizes the highest genetic response for ratio traits. J. Anim. Sci. 95, 1921–1925. https://doi.org/10.2527/jas2016.1324.

Zhang, X., Wang, W., Mo, F., La, Y., Li, C., Li, F., 2017. Association of residual feed intake with growth and slaughtering performance, blood metabolism, and body composition in growing lambs. Sci. Rep. 7, 1–11. https://doi.org/10.1038/s41598-017-13042-7.