Genetic improvement of wool production in Spanish Merino sheep: genetic parameters and simulation of selection strategies

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Abstract. Wool production of the Spanish Merino breed was analysed after several decades of genetic selection to improve meat production. Genetic parameters (heritability and correlations) were estimated for greasy fleece weight, staple length, crimp frequency and fibre diameter of 1869 Spanish Merino purebred sheep. Heritabilities ranged from 0.08 ± 0.050 (fibre diameter) to 0.22 ± 0.060 (staple length), and the genetic correlations ranged from −0.63 ± 0.159 (crimp frequency – staple length) to 0.75 ± 0.222 (fibre diameter – staple length). Genetic simulations were developed to show the consequences of eight selection strategies, which included single trait selection on wool traits and liveweight (the current selection criteria) and index selection combining traits. The results showed that it is possible to improve wool and growth traits at the same time. Also, our results show there is indirect genetic progress for wool characteristics using the current liveweight selection criterion.

Introduction

Wool has been, and still is, the most important production characteristic of many sheep breeds in the world. Historically, most of the wool producing breeds are derived from the Merino branch. Spanish Merino sheep constitute a population with genetic influence over many other breeds around the world. In fact, the Merino breed dominates mutton production in Australia. The Merino breed contributes more than 50\% of the genes among lambs slaughtered annually in Australia (Fogarty \textit{et al.} 2003). The use of wool fibre substitutes and the huge development of artificial fibres influenced, in a negative way, wool market and the profitability of Merino in Spain. As a consequence of this crisis, in the 1970s to 1980s, the Spanish Merino Breeders’ Association created the National Selection Nucleus, formed by the purest and most selected flocks, and changed the production orientation of Spanish Merino sheep, looking for an improvement in meat production traits (Barajas 2002). The current Spanish Merino Genetic Selection Plan aims at quantitative and qualitative improvement of meat production, maintaining the breed’s toughness and morphological characteristics. The breeding criterion is the improvement of maternal traits in the harsh environmental conditions where Merino sheep live. Those traits are determined on the basis of the dams’ rearing capacity, measured according to growth of the lambs up to 30 days, and on the numerical productivity, measured by recording age at first birth, interval between births, prolificity and number of lambs weaned by the dam (Sierra \textit{et al.} 1998). Now, after 25 years of selection, data from 193 792 animals have been compiled. The National Breed Association believes it is important to maintain wool characteristics as a guarantee for the future in case wool recovers its value (Rodero \textit{et al.} 2001).

However, wool production of Spanish Merino sheep is not routinely controlled.

The main objectives of this study were:

• to establish, for first time, the genetic parameters for Spanish Merino wool traits;
• to determine the current genetic situation of wool production of Spanish Merino sheep after decades of genetic selection for meat production; and
• to simulate the repercussion of different selection strategies on wool traits for future selection alternatives if the wool returns to recover its value in Spain.

Material and methods

Spanish Merino has traditionally been reared following a very extensive system, and feed was confined to levels that sheep would obtain during grazing. For this reason, the one birth per year was made to coincide with times of abundance in the pastures. Merino’s orientation to meat production has gone hand in hand with an intensification of the productive and reproductive system, and additional feed is provided in times of fodder shortages.

Wool samples were collected from the shoulder and from the hip at shearing. Greasy fleece weight (GFW), staple length (SL), crimp frequency (CF) and fibre diameter (FD) data were obtained from 1869 Spanish Merino purebred sheep from the National Selection Nucleus, born between 1995 and 2002 (1 to 8 years old) from 20 purebred flocks. Of these, 1479 were females and 390 males, 87.05\% (1328 ewes and 299 rams) were adult animals and 12.95\% (151 females and 91 males) were between 12 and 23 months old. At shearing time, most ewes (>95\%) were not pregnant or in their first month of pregnancy and pregnancy had no influence on their wool quality. Wool samples were analysed...
using Spanish Standard Methods (IWTO 1997). FD was measured using a diameter analyser (Projection Microscope). This method establishes the use of a minimum of 100 fibres per sample. A staple length tester was used to measure SL and CF.

Estimates of (co)variance components for each wool trait were obtained by REML procedures fitting an animal model. The linear mixed model fitted for all traits included flock (20 levels), birth year (eight levels of age: 1 to 8 years), type of lamb birth (three levels: single, twin, multiple), age group–sex interaction (four levels: male/female x hogs/adults) as fixed effects and the genetic additive effects as random effect:

\[ y = xb + Za + e \]

where 'y' is the observation with the vector of fixed effects (b), direct genetic effects (a), and random residual effects (e). The incidence matrix, 'Za', relates the random effect to the observation (y).

The multi-trait models were achieved by extending individual models with the inclusion of appropriate covariance between random terms.

The pedigree used to form the \( A^{-1} \) relatedness coancestry matrix for the random animal effects involved 2257 animals and included three generations (great-grandparents). This information was compiled from the Spanish Merino Stud Book. The reproductive managing of the flocks from the National Selection Nucleus follows a controlled tupping system. Each ram stays with 30 hogs/adults as 

\[ \text{Simulations were developed for a 200 ewe flock. The across age flock structure proceeds from population demographic parameters obtained in Spanish Merino (weaning rate: 0.95; survival rate: 0.9; male : female mating ratio: 1 : 25; first drop males = 2, females = 2; last drop males = 7, females = 10). Genetic responses were calculated following a classic approach (Falconer 1990):} \]

\[ r = (msi + fsi) \div (mgi + fgi) \times h^2 \times sd \]

where \( r \) is response; \( msi \) is male selection intensity; \( fsi \) is female selection intensity; \( mgi \) is male generational interval; \( fgi \) is female generational interval; \( h^2 \) is heritability; and \( sd \) is phenotypic standard deviation.

Following a classic approach, the selection index (b) was calculated using the values from the variance and covariance matrices (P and G, respectively), and the economic weight (a). Thus, the selection index was:

\[ b = P^{-1} \times G \times a \]

For selection to improve wool characteristics, using all of the traits at once (Simulation 3) or the two main economic wool traits (FD, GFW) (Simulation 4), an economic coefficient was assigned to each wool trait according to recommendations from the Spanish Merino Breeders’ Association. Economic coefficients assigned to FD, SL, CF, and GFW were −3.5, 1, 0.5, and 5 respectively according to the demands of wool market in Zafra, the main wool market in Spain. To study the effects of selection on liveweight and the two main economic wool traits (Simulation 5), its economic value was taken as 8, while the economic values for wool quality traits (FD, GFW) were −1 and 1 respectively.

**Results**

**Descriptive statistics for the wool traits**

Descriptive statistics for the studied traits are shown in Table 1. The mean for wool traits analysed were 21.3 μm, 6.9 cm, 66.2 crimps/dm (c/dm) and 4.2 kg for FD, SL, CF and GFW, respectively. The coefficient of variation for these traits ranged from 5.3 (FD) to 20.4% (GFW).

**Genetic parameters**

Table 2 shows heritabilities and phenotypic and genetic correlations between wool traits. These are the first genetic parameters obtained for wool traits in Spanish Merino sheep. Heritabilities show mid-low values (\( h^2_{FD} = 0.08; h^2_{SL} = 0.22; h^2_{CF} = 0.11; h^2_{GFW} = 0.13 \)). Phenotypic correlations ranged from −0.77 (FD–CF) to 0.30 (FD–GFW). The highest positive

**Table 1. Descriptive statistics of wool traits in Spanish Merino sheep population**

<table>
<thead>
<tr>
<th>Trait</th>
<th>Mean ± s.e.</th>
<th>Maximum</th>
<th>Minimum</th>
<th>CV</th>
</tr>
</thead>
<tbody>
<tr>
<td>FD</td>
<td>21.3 ± 0.03 μm</td>
<td>25.0 μm</td>
<td>18.0 μm</td>
<td>5.8%</td>
</tr>
<tr>
<td>SL</td>
<td>6.9 ± 0.12 cm</td>
<td>12.0 cm</td>
<td>4.3 cm</td>
<td>14.6%</td>
</tr>
<tr>
<td>CF</td>
<td>66.2 ± 0.03 c/dm</td>
<td>110.0 c/dm</td>
<td>40.0 c/dm</td>
<td>15.1%</td>
</tr>
<tr>
<td>GFW</td>
<td>4.2 ± 0.05 kg</td>
<td>6.2 kg</td>
<td>2.0 kg</td>
<td>20.4%</td>
</tr>
</tbody>
</table>
Table 2. Heritabilities (diagonal), genetic correlations (above diagonal) and phenotypic correlations (below diagonal) of wool traits in Spanish Merino sheep population

FD, fibre diameter; SL, staple length; CF, crimp frequency; GFW, greasy fleece weight

<table>
<thead>
<tr>
<th>Trait</th>
<th>FD (µm)</th>
<th>SL (cm)</th>
<th>CF (crimps/dm)</th>
<th>GFW (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FD</td>
<td>0.08±0.049</td>
<td>0.75±0.222</td>
<td>–0.57±0.254</td>
<td>–0.06±0.041</td>
</tr>
<tr>
<td>SL</td>
<td>0.18±0.023</td>
<td>0.22±0.060</td>
<td>–0.63±0.159</td>
<td>0.01±0.024</td>
</tr>
<tr>
<td>CF</td>
<td>–0.77±0.051</td>
<td>–0.22±0.023</td>
<td>0.11±0.050</td>
<td>0.48±0.145</td>
</tr>
<tr>
<td>GFW</td>
<td>0.30±0.060</td>
<td>0.26±0.061</td>
<td>–0.27±0.062</td>
<td>0.13±0.078</td>
</tr>
</tbody>
</table>

genetic correlation was 0.75 (FD–SL), whereas the highest negative genetic correlation was –0.63 (CF–SL).

Simulation of genetic selection response

Spanish Merino current selection plan (liveweight selection; Simulation 1)

The current Spanish Merino Selection Plan aims to improve growth and meat production using average daily gain from birth to weaning and to slaughter as the main criteria.

The objective of the first simulation was to show the effect of this growth selection on wool traits. According to our results (Table 3), the current Growth Selection Plan is not resulting in a decline in wool quality, rather it is resulting in a slight improvement in FD, GFW, CF and SL.

Effect of selection on a single wool trait (Simulation 2)

Direct response (per generation) in each trait and correlated indirect response in other wool traits were estimated (Table 3). The direct response on FD selection would be a decrease of 0.157 µm/generation. As an indirect response, when reducing FD, a decrease in SL and an increase in CF and GFW would be observed. The direct response on SL selection would be an increase of 0.231 cm/generation and, as indirect effect, there would be an increase in FD and a decrease in CF and GFW. It would be possible to obtain a direct response if selection were done for CF, increasing 1.617 c/dm.generation. As an indirect response, FD and SL would decline and GFW would increase slightly. GFW genetic response would get an increase on this trait of 0.140 kg/generation. Indirectly, FD and SL would diminish and CF would increase.

Effect of simultaneous selection for the four wool traits (Simulation 3)

A selection index has been developed to combine the four wool production traits, using genetic parameters estimated in this work:

\[ I = -0.28 \times FD + 0.21 \times SL + 0.05 \times CF + 0.65 \times GFW \]

Results show an important reduction in FD (–0.100 µm) and an increase of GFW (0.123 kg) and CF (1.556 c/dm). SL would lose 0.158 cm (Table 4).

Effect of selection on the two main economic wool traits for wool industry (Simulation 4)

Given that GFW and FD account for around 90% of the value of individual fleeces, they are logical breeding objectives for Merino breeding programs focussed on maximising improvement in profit (Taylor and Atkins 2000). The selection index for these two traits was:

\[ I = -0.4 \times FD + 0.65 \times GFW \]

The direct response in GFW and FD and the indirect response in SL and CF are shown in Table 4. Results show greater decreases in FD than in the previous simulation (selection for the four wool traits), but smaller increases in GFW (0.119 kg). As an indirect response, SL would decrease (–0.162 cm) more than in the previous strategy and the increase of CF would be lower as well (0.110 crimps less).

Selection plan on liveweight and the two main economic wool traits (Simulation 5)

The last strategy simulates Spanish Merino sheep selection taking into account WW, as well as wool traits GFW and FD. The optimum selection index was:

\[ I = -0.08 \times FD + 0.13 \times GFW + 2.4 \times WW \]

As a direct response, WW would increase 0.737 kg, GFW 0.06 kg, SL 0.015 cm, and CF 0.206 c/dm; FD would decrease 0.021 µm (Table 4).

Discussion

Wool traits have not been selected in this breed for several decades, but wool of Spanish Merino Sheep maintains a medium–high

Table 3. Simulated direct and correlated responses (per generation) to selection for weaning weight or single wool traits in Spanish Merino sheep

FD, fibre diameter; SL, staple length; CF, crimp frequency; GFW, greasy fleece weight; WW, weaning weight

<table>
<thead>
<tr>
<th>Trait</th>
<th>WW</th>
<th>FD</th>
<th>SL</th>
<th>CF</th>
<th>GFW</th>
</tr>
</thead>
<tbody>
<tr>
<td>FD (µm)</td>
<td>–0.014</td>
<td>–0.157</td>
<td>0.146</td>
<td>–0.099</td>
<td>–0.036</td>
</tr>
<tr>
<td>SL (cm)</td>
<td>0.026</td>
<td>–0.215</td>
<td>0.231</td>
<td>–0.175</td>
<td>–0.063</td>
</tr>
<tr>
<td>CF (crimps/dm)</td>
<td>0.199</td>
<td>1.017</td>
<td>–1.230</td>
<td>1.617</td>
<td>1.261</td>
</tr>
<tr>
<td>GFW (kg)</td>
<td>0.050</td>
<td>0.032</td>
<td>–0.038</td>
<td>0.190</td>
<td>0.140</td>
</tr>
<tr>
<td>WW (kg)</td>
<td>0.743</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4. Genetic response by generation in wool traits based on use of selection indexes in Spanish Merino sheep

FD, fibre diameter; SL, staple length; CF, crimp frequency; GFW, greasy fleece weight; WW, weaning weight

<table>
<thead>
<tr>
<th>Trait</th>
<th>WW</th>
<th>FD</th>
<th>SL</th>
<th>CF</th>
<th>GFW</th>
</tr>
</thead>
<tbody>
<tr>
<td>FD (µm)</td>
<td>–0.100</td>
<td>–0.112</td>
<td>–0.021</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SL (cm)</td>
<td>–0.158</td>
<td>–0.162</td>
<td>0.015</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CF (crimps/dm)</td>
<td>1.556</td>
<td>1.466</td>
<td>0.206</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GFW (kg)</td>
<td>0.123</td>
<td>0.119</td>
<td>0.060</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WW (kg)</td>
<td>0.737</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
quality fineness grade. Their low coefficients of variation agree with centurie of fine wool selection. It is accepted that fleece and fibre traits are very fixed in the Merino breed (Esteban et al. 1998).

The obtained genetic parameters are in general low, due to the fact that the animals used in this study come from the National Selection Nucleus, the most selected flocks in Spain. The almost-closed breeding system of these flocks, combined with centuries of selection for wool production, has decreased the variability of wool traits. Thus, as a result, their heritability and genetic correlation magnitudes have decreased. Moreover, the population has got a high degree of consanguinity. These facts complicate the selection, but they can be positive for the homogeneity of wool production.

Heritability estimates in this study are within the range, but closer to the lower limit, of estimates for other Merino sheep obtained from individual animal models (see Safari and Fogarty 2003; Safari et al. 2005, 2007). Thus, GFW ($h^2 = 0.13$) and SL ($h^2 = 0.22$) values observed in our study were lower than for other studies, but higher than those reported by Nagy et al. (1999). Those differences are due to the production system used by the Spanish Merino’s breeders, more focussed on the sale of rams and ewes than on lamb or wool production. Therefore the main aim of the selection is the morphology, followed by the growth of lambs. The common inbreeding system, used to fix the morphological traits of the most valued breeding animals, has led to a low genetic variability in comparison to Merinos from other countries. Those two reasons explain the divergence between our data and those reported by other authors.

Genetic correlations in the Spanish Merino breed are within the reported range (see Safari and Fogarty 2003; Safari et al. 2005, 2007) but some magnitudes were closer to the lower limits. Thus, the genetic correlation between FD and SL reported by other authors and found in this study were always positive. On the other hand, the previously reported FD–GFW and SL–GFW genetic correlations were generally higher than those obtained in this study, with the exception of Nagy et al. (1999) and Hill (2001), who reported lower FD–GFW correlation values, and Swan et al. (1995) and Brown et al. (2002), who reported lower SL–GFW correlation values.

Phenotypic correlations were higher than additive ones, with the exception of SL–CF and CF–GFW, indicating a relatively large residual correlation, as reported by Fogarty (1995) for correlation between FD and GFW.

The textile industry values easy spinning and low diameter fibres. In our study we have found that the FD of wool from the studied animals would be classed between fine and medium wool (I and II classes in Spanish classification). Its low coefficient of variation and heritability ($h^2 = 0.08$) makes difficult the improvement of this trait, although the increasing demand for ‘super-fine’ wools makes this study necessary.

Although Spanish Merino’s Selection Plan is aimed at meat production, it has improved morphological uniformity of animals, erasing skin folds and increasing fleece weight. However, Spanish Merino’s fleece weight is far from that of Australian Merino. That difference is partly due to Australian Merino’s higher liveweight and to the high correlation between live and fleece weights, around 0.55 according to Cardellino et al. (2001), Brown et al. (2002) and Safari and Fogarty (2003). This means that selection to increase both liveweight and wool production could be successful. The optimum selection plan for Spanish Merino breed should tend to increase the live weight, to decrease the FD and to increase the fleece weight, acting against the negative correlation between FD and fleece weight. Some studies show that it may be achieved (Wuliji et al. 1999). However, the response from that multi-trait selection depends on the studied breed (Gizaw et al. 2007). In our case, a simulation with selection on live weight and the two main economic wool traits (FD and fleece weight) showed similar results to the current Spanish Merino Selection Plan but with a slight gain in wool traits at the expense of live weight.

Significant progress in FD can be achieved while maintaining or slightly increasing live and fleece weight. That may help to diversify Merino wool production according to the ultimate use of wool with regards to its FD, but subject to other wool traits (Wuliji et al. 1999). Safari et al. (2006) studied the response of multi-trait index selection in sheep and reported that genetic responses in fine wool selection were highly sensitive to the correlation between live weight and FD. Intense selection to reduce FD can result in genetic progress of 0.36 μm/year in high quality fibre with a slight decrease in fleece weight (Sherlock and Garrick 1995). Finally, Kelly et al. (2007) reported that single-trait selection on FD would reduce FD, fleece and live weight but would not significantly impact on reproduction traits.

Wool SL becomes of great importance in the textile business. Only the finest and longest fibres are combed. SL obtained in Spanish Merinos is lower than those found in the derivative breeds (Unal 1995; Esteban et al. 1998; Hatcher 2000), and this must be taken into account in genetic improvement of Merino wool production.

Although CF is not included in the calculation of the economic value of wool, it is important in the manufacturing performance during the spinning stage because the ‘bulk’ is a trait very valued in the wool market. However, it has a negative correlation with FD and a moderate heritability.

We have found that GFW has a high coefficient of variation, moderate heritability, and positive correlation with other wool traits, especially with clean fleece weight (around 0.9 according to Safari and Fogarty 2003). This means that selection for GFW may be used to increase wool production in this breed.

Our results agree with those obtained by Atkins (1997) who, by selecting for increased SL and reduced CF, obtained a large response in SL and a positive light correlation with yield and fleece weight, and a slight increase of FD. These results are also similar to those obtained by Cardellino et al. (2001).

If Spanish wool producers intend to become competitive in the international market, wool quality and production, as well as trade structures should be improved.

Conclusions

Genetic parameters calculated for the first time in Spanish Merino sheep indicate that simultaneous improvement of live weight and wool traits can be achieved in this breed. However, the low heritabilities and genetic correlations shown in this study require careful consideration, indicating that small additive genetic improvements in these traits may be possible but with difficulties.

Genetic antagonisms among economically important wool traits seem to exist only between SL and CF. That antagonism and
the positive genetic correlation between FD and SL require explicit attention in development of selection programs for wool improvement.

The availability for the first time of reliable phenotypic and genetic parameter estimates in Spanish Merino sheep would enable the formulation of a selection index that would maximise the genetic gain taking into account correlated traits. Therefore, although Spanish Merino Selection Plan cannot be oriented to wool production because of current low wool value, our results show it would be possible to improve wool traits within a Selection Plan oriented to meat production. If it were necessary to make wool competitive again, the FD and GFW would be able to be included into the Spanish Merino’s Selection Plan. The output of the study could also be utilised to evaluate and develop optimum alternative improvement of multi-trait (meat–wool) aptitude.

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