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Variation in the whiteness and brightness of mohair associated with farm, season, and mohair attributes

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Short title: Variation in colour attributes of mohair
Abstract

This work aimed to quantify factors affecting the reflectance attributes of Australian white mohair sourced from five different farms and to evaluate the effect of season and year on mohair grown by goats of known genetic origin in a replicated study. For the season study the mohair was harvested every three months for two years. All goats and their fleeces were weighed. Mid-side samples were tested for fibre diameter attributes, clean washing yield (CWY), staple length (SL) and for tristimulus values X, Y, Z and Y-Z. For the farm study (n=196), linear models, relating Y, Z and Y-Z were fitted to farm of origin and other objective measurements. For the season and year study (n=176), data were analysed by ANOVA and then by linear analysis. The variation accounted for by farm alone was: X, 22%; Y, 24%; Z, 12%; Y-Z, 30% (P<0.001). Once farm had been taken into account, the regression models for X, Y and Z had similar significant terms: mean fibre diameter (MFD), CWY, SL and fibre diameter CV; and correlation coefficients (0.57-0.65). For Y-Z, in addition to farm only MFD was significant (P=1.8 × 10^-9). While X, Y, Z and Y-Z were significantly associated with clean fleece weight (CFwt), CFwt was not significant in any final model. Season affected mohair Y (P=2.5 × 10^{-24}), Z (P=2.3 × 10^{-20}) and Y-Z (P=6.8 × 10^{-22}). Autumn grown mohair had higher Y and Z, and summer grown mohair had lower Z than mohair grown in other seasons. This resulted in summer grown mohair having the highest Y-Z and winter grown mohair having the lowest Y-Z than mohair grown in other seasons. The differences between years in Y, Z and Y-Z were significant but not large. When Y, Z and Y-Z were modeled with season and other mohair attributes, MFD, CWY, CFwt, incidence of medullated fibre (Med) and sire were also significant terms. This model accounted for 62.1% of the variance. Over the range of Med (0.3-4.2%), Y-Z increased by 11 T units. Increasing CFwt 0.5 kg was associated with a decline in Y-Z of 7.5 T units. The variation in Y, Z and Y-Z associated with sire effects were respectively 2.66, 3.77 and 1.04 T units. In the farm and the season studies increasing MFD was associated with lower Y and Z and higher Y-Z. The extent of the differences in tristimulus values between seasons and years, were unlikely to be of commercial importance. The extent of the differences between farms, and to variations in MFD and Med were large enough to be of commercial importance. Clean mohair colour was artefactually biased by MFD.
Keywords: Brightness; Colour measurement; Diameter-scatter; Reflectance; Sire; Wool colour;

Yellowness
1. Introduction

Mohair forms the long lustrous coat of the Angora goat. Mauersberger (1954), von Bergen (1963), Evans (1984) and Hunter (1993) have described the evolution of mohair in world textile trade since about 1920. The most important commercial attribute of mohair is its mean fibre diameter, which explains over 50% of the variation in auction prices (McGregor and Butler, 2004). Other fibre attributes of commercial importance include staple length, style, freedom from contaminants such as vegetable matter and the incidence of medullated fibres.

Mohair is famed for its natural lustre which can be measured objectively by visible light reflectance at a range of observation angles, although there is some debate about the best methods (Hunter, 1993). The main explanation given for the high lustre of mohair is the relatively large surface cuticle scales, and the low cuticle scale edge height relative to other animal fibres, which results in a lustre peak reflection. However, lustre and yellowness of mohair may be correlated to the extent that processes which lead to yellowing are also associated with declines in lustre (Strydom, 1975). Lustre is not measured prior to commercial sales of mohair or wool. The reflectance properties of wool are assessed prior to sales using international standards (IWTO-14, 2005d). These methods describe the colour of an object in terms of tristimulus values (T units), where X refers to reflected red light, Y refers to reflected green light and Z refers to reflected blue light. Higher Y values indicate greater brightness (or lightness). Lower differences between the Y and Z values (Y-Z) indicate greater whiteness and higher differences greater yellowness. Perfectly white fibre would have Y = 100 and a Y-Z = 0 (Wood, 2002; Hatcher et al., 2010). White mohair is preferred by processors, as it can be dyed to a greater range of colours. Millington (2006a,b) provides comprehensive reviews of factors affecting photodegradation of wool, factors which are likely to affect mohair. Exposure to UV light present in sunlight causes photo-bleaching, followed by progressive photo-yellowing and after a few months, the wool undergoes photo-tendering, characterized by reduced tensile strength.

While Taddeo et al. (2000) examined the variation in Y and Y-Z across the mohair fleece, no reports on factors associated with variation in colour attributes of white mohair have been located. As the variation in the colour attributes of white Merino of wool is of commercial importance
(Woolcheque, 2012), investigations into factors affecting the colour attributes of white mohair are warranted. The present work aimed to quantify the on-farm factors which affect the Y, Z and Y-Z of white Australian mohair.

2. Materials and methods

2.1. Influence of farm

Samples to test the effect of farm were obtained from commercial mohair farms which participated in a national mohair enterprise benchmarking study (McGregor, 2010; McGregor and English, 2010). The farms used in the present study \((n = 5)\) originated from different geographical areas of Australia. Mohair farmers selected a sample of Angora goats, covering a range in ages within their herds, for regular monitoring and fleece sampling. Mohair harvested during the autumn 2006 shearing was used in this study and represents the fibre grown over the previous six-month period. Prior to shearing, all goats were weighed to the nearest 0.5 kg. At shearing, fleeces, pieces, bellies and locks and samples were weighed to the nearest 10 g to provide the greasy fleece weight. Mid-side samples were taken at shearing, identified and stored in a plastic bag. Mid-side samples were used as Taddeo et al. (2000) concluded that the mid-rib site best represented the mean Y and Y-Z values for the mohair fleece.

Staple length (SL) was determined as the mean of three staples taken from the mid-side sample and measured to the nearest 0.5 cm. Fleece samples were commercially tested for clean washing yield (CWY; %, w/w), mean fibre diameter (MFD; µm), fibre diameter coefficient of variation (CVD; %), fibre curvature (FC; °/mm) and incidence of medullated fibres (Med; %, number) (IWTO, 2005a,b,c). Samples were tested for X, Y and Z tristimulus values (IWTO, 2005d). Clean mohair production per goat (CFwt) was determined as: CWY (as a proportion) \(\times\) greasy fleece weight.

2.2. Influence of season and year
Samples to test the effect of season were obtained from a replicated experiment which included three
different genetic strains. The mohair assessed in this report relates only to the treatment shorn every 3
months \((n = 24)\) between February 2004 and February 2006. Details of the allocation, management
and productivity of the experimental goats have been provided by McGregor and Butler (2008). In
brief, Angora wether goats (18 months of age) were grazed as one flock at Attwood, Victoria
\((37°40’S, 144°53’E,\) altitude 135 m) on annual temperate pastures. The goats were progeny of various
genetic sire lines including 100% South African origin \((n = 2)\), 100% Texan origin \((n = 3)\), and mixed
origin sires approximately 50% South African and 50% Texan \((n = 4)\). Shelter was available in the
form of covered and enclosed shedding that was always accessible and could accommodate all goats.
Fleece sampling and testing was as described earlier and with assessment for staple definition (clarity
of staple formation based on cross fibres), staple tip shape (staple length uniformity based on shape of
the staple tip), style (number of twists along the staple), character (number of crimps along the staple)
and staple fibre entanglement (degree of staple fibre entanglement and fibre adhesions) (McGregor
and Butler, 2008).

2.3. Statistical analyses

Data were analysed to determine parameter means and standard deviations. Box plots are provided for
Y and Y-Z showing the mean, quartiles and outliers for each farm. The effect of farm of origin
(treated as a factor) and other continuous variables on X, Y, Z and Y-Z were determined using general
linear analysis (GenStat 14.1 for Windows; Payne, 2011). The best models were developed
independently with terms being added or rejected on the basis of Wald \(F\)-test. The observational unit
in each analysis was an individual fleece sample. The original farm identifiers have been retained to
enable comparison with previously published data. Standard error of differences between means
(s.e.d.) and least significant differences (l.s.d.), at \(P = 0.05\), are provided. Predicted responses of X, Y,
Z and Y-Z to significant terms, after adjustment for other terms in the models, are provided (GenStat
14.1; Payne, 2011).
The effect of season and year was analysed using restricted maximum likelihood (REML, GenStat 14.1 for Windows; Payne, 2011) by assigning the terms season and year as follows: autumn, for mohair harvested in May; winter, for mohair harvested in August; spring, for mohair harvested in November; summer, for mohair harvested in February; Year 2004, for mohair grown between February 2004 and February 2005; Year 2005, for mohair grown between February 2005 and February 2006. Data from two animals have been omitted as samples were not available for the entire period. The data for season were then analysed using general linear analysis (GenStat 14.1 for Windows; Payne, 2011) to test season, year, sire and other continuous variables, with models and outputs treated as for the farm analyses.

3. Results

3.1. Effect of farm and fleece attributes

The location of the farms, their climatic zone, rainfall and the greasy mohair production of goats which provided fleece samples are provided in Table 1. The mean, s.d. and range in variables are presented in Table 2 and Fig. 1. Mohair originated from goats aged between 0.5 and 4.5 years of age. Mean attributes (range) were: live weight at shearing 30.4 kg (9.8-57.5 kg); greasy fleece weight 2.1 kg (0.5-3.8 kg); CWY, 82.6% (66.4-95.7%); SL, 11 cm (6–16.5 cm); MFD, 29.8 µm (19-41 µm); FC, 14 °/mm (9-22 °/mm); Y, 68 T units (60.4-75.5 T units); Y-Z, 7.6 T units (5.6-10.1 T units).

Farm alone accounted for 22% of the variation in X, 24% of the variation in Y, 12% of the variation in Z and 30% of the variation in Y-Z \((P<0.001)\). Once farm had been taken into account, the regression models for X, Y and Z had similar significant terms and correlation coefficients (Table 3) and for significant terms the magnitude of the regression constants were similar in each regression model (Table 4). The effect of MFD on X, Y, Z and Y-Z after adjustment for the effects of farm and the other terms in the model, are shown in Fig. 2.
For Y, CWY alone accounted for 21% of the variation. When CWY was added to farm an
additional 7.1% of the variance in Y was taken into account. CVD added a further 7.2%, SL added
1.9% and MFD 1.2% to the variance observed. Total variance accounted for was 41.4%, standard
error was 2.13. No other variable was significant (age of goat, \( P = 0.87 \); FC, \( P = 0.51 \); greasy fleece
weight, \( P = 0.73 \); live weight, \( P = 0.64 \); Med, \( P = 0.41 \)). No squared term or product of significant
terms was significant (\( P > 0.1 \)).

Once MFD, CVD, CWY and SL had been accounted for, the mohair from farm 7 had
significantly higher Y (\( P < 0.001 \)) than mohair from farms 9 and 12 which in turn had significantly
higher Y than farms 4 and 5 (\( P < 0.01 \)). The effect of CWY, CVD and SL on Y, after adjustment for
the effects of farm and the other terms in the model, are shown in Fig. 3. For each 10% units increase
in CWY, Y increased 1.8 T units, for each 10% increase in CVD, Y increased 1.3 T units, for each 4
cm increase in SL, Y decreased 1 T unit and for each 10 \( \mu \)m increase in MFD, Y decreased 0.8 T units
(Table 4).

For Z, CWY alone accounted for 11% of the variation. When CWY was added to farm an
additional 7.4% of the variance in Z was taken into account. MFD added a further 8.9%, CVD added
3.1% and SL 1.3% to the variance observed. Total variance accounted for was 32.7%, standard error
was 2.64. No other variable, squared term or product of significant terms was significant (\( P > 0.1 \)).

Once MFD, CVD, CWY and SL had been accounted for, the mohair from farm 7 had significantly
higher Z (\( P < 0.05 \)) than mohair from farm 5, with farms 4, 9 and 12 not differing from farm 5 or farm
7. For each 10 \( \mu \)m increase in MFD, Z decreased 1.5 T units, for each 10% units increase in CWY, Z
increased 1.9 T units, for each 10% increase in CVD, Z increased 1.4 T units and for each 4 cm
increase in SL, Z decreased 1 T unit (Table 4).

For X, the prediction models were very similar to those for Y and Z (Table 4). When CWY
was added to farm an additional 6.9% of the variance in X was taken into account. CVD added a
further 7.3%, SL added 1.7% and MFD 1.3% to the variance observed. Total variance accounted for
was 39.4%, standard error was 2.04. No other variable, squared term or product of significant terms
was significant (\( P > 0.1 \)). Once MFD, CVD, CWY and SL had been accounted for, the mohair from
farm 7 had significantly higher X (\( P < 0.05 \)) than mohair from all farms except farm 9, and there were
no other significant differences between with farms. For each 10 µm increase in MFD, X decreased 0.9 T units, for each 10% units increase in CWY, X increased 1.7 T units, for each 10% increase in CVD, X increased 1.2 T units and for each 4 cm increase in SL, X decreased 0.9 T units (Table 4).

Once farm had been taken into account, only MFD was significant in affecting Y-Z (Table 3). MFD alone accounted for 16.5% of the variation in Y-Z and when added to farm accounted for an additional 12.1% to the variance observed (total variance accounted for was 42.5%, standard error was 0.711). No other variable nor MFD² was significant (CWY, \( P = 0.58 \); CVD, \( P = 0.079 \); FC, \( P = 0.99 \); SL, \( P = 0.69 \); age, \( P = 0.90 \); greasy fleece weight, \( P = 0.41 \); live weight, \( P = 0.72 \); Med, \( P = 0.48 \)). No squared term or product of significant terms was significant \( (P > 0.1) \). Including MFD in the analysis with farm indicated that mohair from farm 5 had significantly higher Y-Z \( (P < 0.001) \) than farm 12, with farms 7 and 9 being intermediate between farms 5 and 12, while farm 4 had significantly lower Y-Z than all other farms \( (P < 0.001) \). The effect of MFD on the Y-Z after adjustment for the effects of farm is shown in Fig. 2d. For each 10 µm increase in MFD, Y-Z increased 0.8 T units (Table 4).

For X, there was a significant association \( (P = 0.013, r = -0.16) \) with CFwt indicating that X decreased 0.81 (s.e. 0.32) T units for each kg increase in CFwt. For Y, there was a significant association \( (P = 0.041, r = -0.13) \) with CFwt indicating that Y decreased 0.70 (s.e. 0.34) T units for each kg increase in CFwt. For Z, there was a significant association \( (P = 0.008, r = -0.18) \) with CFwt indicating that Z decreased 1.01 (s.e. 0.38) T units for each kg increase in CFwt. For Y-Z, there was a significant association \( (P = 0.017, r = 0.15) \) with the CFwt indicating that Y-Z increased 0.31 (s.e. 0.13) T units for each kg increase in CFwt. However, CFwt was not significant in the final models for X, Y, Z and Y-Z (Table 3).

### 3.2. Effect of season, year and mohair attributes

The mean, s.d. and range in variables are presented in Table 5. Mean and range of some mohair attributes for the three month growing periods were: greasy fleece weight, 1.23 kg (0.50-2.34 kg);
CWY, 85.9% (67.0-96.7%); SL, 7.2 cm (5.0–11.5 cm); MFD, 32.1 µm (21-41 µm); Y, 70.2 T units (62.9-76.4 T units); Y-Z, 8.0 T units (5.5-10.5 T units).

Y was significantly affected by an interaction between season and year (s.e.d. 0.46; $P = 2.9 \times 10^{-9}$, Table 6). The main effect of season was large, with autumn grown mohair having higher Y and summer grown mohair lower Y than mohair grown during other seasons ($P = 2.5 \times 10^{-24}$, Table 6). Mohair grown in Year 2005 had higher Y than mohair grown in Year 2004 (71.3 versus 69.1 T units; s.e.d. 0.23; $P = 8.2 \times 10^{-19}$).

Z was significantly affected by an interaction between season and year (s.e.d. 0.46; $P = 0.028$, Table 6). The main effect of season was large, with autumn grown mohair having higher Z and summer grown mohair lower Z than mohair grown during winter and spring ($P = 2.3 \times 10^{-20}$, Table 6). Mohair grown in Year 2005 had higher Z than for mohair grown in Year 2004 (63.4 versus 60.8 T units; s.e.d. 0.27; $P = 1.6 \times 10^{-17}$).

Y-Z was significantly affected by an interaction between season and year (s.e.d. 0.17; $P = 1.7 \times 10^{-18}$, Table 6). Mohair grown in autumn 2004 and both summers had higher Y-Z than mohair grown during the other seasons ($P < 0.05$, Table 6). The mohair with the lowest Y-Z was grown in winter 2004 ($P < 0.05$). The main effect of season was large, with each season having a different Y-Z, and the summer and autumn Y-Z being higher than the winter and spring Y-Z ($P = 6.8 \times 10^{-22}$, Table 6). Mohair grown in Year 2004 had higher Y-Z than for mohair grown in Year 2005 (8.16 versus 7.92 T units; s.e.d. 0.085; $P = 0.005$).

When Y was modeled with season and other mohair attributes the following terms were significant: season ($P = 3.1 \times 10^{-16}$); year ($P = 7.9 \times 10^{-17}$); sire ($P = 0.008$); product of MFD × Med ($P = 9.8 \times 10^{-6}$); square of Med ($P = 0.00078$); product of CWY × Med ($P = 0.003$). This model accounted for 63.0% of the variance and the residual standard error was 1.63. Neither square or products of significant terms not listed above or other terms were significant ($P > 0.1$). The main effect of increasing MFD and Med are shown in Fig. 4a and d. Increasing CWY led to increased Y.

The variation in Y associated with sire effects, after accounting for other terms in the model, was a range of 2.66 T units.
When Z was modeled with season and other mohair attributes the following terms were significant: season \((P = 5.9 \times 10^{-19})\); year \((P = 1.0 \times 10^{-14})\); sire \((P = 5.6 \times 10^{-5})\); product of MFD \(\times\) Med \((P = 1.4 \times 10^{-7})\); square of Med \((P = 0.00091)\); product of CWY \(\times\) Med \((P = 0.017)\). This model accounted for 65.7% of the variance and the residual standard error was 1.70. Neither live weight at shearing, clean fleece weight, CVD, SL, square and products of significant terms not listed above or other terms were significant \((P > 0.05)\). The main effect of increasing MFD and Med are shown in Fig. 4b and c. Increasing CWY led to increased Z. The variation in Z associated with sire effects, after accounting for other terms in the model, was a range of 3.77 T units.

When Y-Z was modeled with season and other mohair attributes the following terms were significant: season \((P = 1.8 \times 10^{-14})\); product of MFD \(\times\) Med \((P = 1.2 \times 10^{-6})\); character \((P = 0.00011)\); cube of CFwt \((P = 0.00020)\) and sire \((P = 0.003)\). Other terms, including live weight at shearing, year, CWY, CVD, staple tip definition and SL, were not significant \((P > 0.05)\). This model accounted for 62.1% of the variance and the residual standard error was 0.587. Increasing MFD (Fig. 4c) and Med (Fig. 4f) were associated with increases in Y-Z. After accounting for other terms in the model, increasing character by 10 crimps was associated with an increase in Y-Z of 1.5 T units and increasing CFwt 0.5 kg was associated with a decline in Y-Z of 7.5 T units and the variation in Y-Z associated with sire effects was a range of 1.04 T units.

4. Discussion

Y, Z and Y-Z of white Australian mohair were affected by farm of origin, season of growth and genetic background. In addition, the Y and Z of mohair increased with increases in CWY and CVD and declined with increases in SL and MFD. The Y-Z of mohair increased as MFD and Med increased.

4.1. Effects of farm and mohair attributes
As reported for cashmere, variation between farms in the reflectance attributes of mohair may reflect differences between farms in: geographic and climatic factors; productivity of the goats; consumption by goats of different nutrients and plants; and genetics (McGregor, 2012).

It is likely that the farms which supplied the mohair experienced different levels of solar radiation given the differences in latitude, altitude and climate of the farms (Godar, 2005; Table 1). Differences in the ambient temperatures between farms may also alter sweating (suint production) which is also associated with yellowing of wool. Such an effect is likely to be part of the CWY effect.

One mechanism for differences in Y and Y-Z between farms could be differences in the relative dilution of natural chromophores within the fleece consequent upon differences in rates of mohair growth (Table 2) similar to the effect detected with cashmere (McGregor, 2012). This would imply that more productive Angora goats produce brighter (higher Y) and whiter (lower Y-Z) mohair. In the between farm study, while there were general associations between Y, Z and Y-Z and mohair production, CFwt was not significant when farm was included in the models. Perhaps, the specific effect of CFwt on Y, Z and Y-Z was included within the farm effect (Table 3). However, in the controlled effect of season study, increasing CFwt was associated with significant reductions in Y-Z suggesting that there was a dilution effect on natural chromophores.

An important fibre quality measurement related to evaluating the productivity of Angora goats and the value of mohair is the MFD of mohair. In both the farm and the season studies, increasing MFD was associated with lower Y and Z and higher Y-Z while in the farm study increasing CVD was associated with higher Y. Wang et al. (2011) found that with 10 wool samples, increasing MFD over the range 13.5-20.3 µm was associated with increases in Y-Z of about 1 T unit and no change in Y. They concluded that the reflectance spectra for wool included information about diameter-related light scattering with measurements showing that the diameter-dependence was stronger for wool Y-Z than for wool Y. This result arose mainly as a result of differences in reflectance in the region < 470 nm, which coincides with the wavelength region largely determining the Z value. As the regression model results for mohair indicate (Table 4), as MFD increases, the Z values decline faster than the Y values leading to a greater difference in the calculations of Y-Z. In the work of Wang et al. (2011) the effects of CWY, CVD or SL were not accounted for and so the reported responses may not fully
estimate the effect of MFD upon Y, Z and Y-Z values. In any case, the conclusion of Wang et al. (2011) that “clean wool colour is artefactually biased by diameter” appears applicable to mohair.

SL was significantly associated with Y and Z of mohair in the farm study but not in the season study. The magnitude of the effect of SL on Y and Z was the same (Table 4) so the net effect on Y-Z was zero. It is interesting that increasing SL was associated with a reduction of Y and Z in the farm study, as it might have been considered that longer SL would provide some protective (shading) advantages to mohair which grew closer to the skin, as is observed with Merino wool. For mohair there are two possible reasons why this effect may not have been detected. Firstly, the mohair fleece has a more open staple structure which may allow greater UV light penetration compared with the Merino fleece. The more open staple structure compared with Merino wool is based on a lower skin follicle density and a reduced number of cross fibres. Perhaps longer mohair provides even less protection against UV light than shorter and more compact mohair. Secondly, in the season study the mohair fleece was shorn every three months rather than annually as practiced with Merino sheep, and season was significant. Clearly the short shearing interval is likely to have precluded SL developing to the extent that any protective effect from shading may become significant.

Part of the farm effect is likely to be related to goats grazing on farms located in different geographic and climatic regions where pastures are composed of different plant communities and grow on different soil types. Thus it is likely that the goats on different farms will ingest different nutrients and plant chromophores. Both the quantity and quality of plant food consumed by goats has been shown to affect the Y, Y-Z and redness (X-Y) of white cashmere (McGregor and Tucker, 2010) changes most likely mediated via changes in the amino acid content of the fibre (McGregor and Tucker, 2010) and perhaps trace metal content of the fibre. Variation in soil type also causes variations in the trace metal content of wool (Fleet et al., 2010).

In both the farm and season studies CWY affected Y and Z of mohair but not the Y-Z. As discussed for SL, the magnitude of the effect of CWY on Y and Z was similar (Table 4) and so the net effect on Y-Z was zero. The mechanism of action of CWY is a likely consequence of changes in the content of suint and wax in the greasy fleece, as increased CWY indicates less natural contaminants. Increasing quantities of wax and suint in raw cashmere have been associated with changed tristimulus
values for raw and processed cashmere (McGregor and Tucker, 2010; McGregor, 2012) and raw and processed wools (Hoare and Stewart, 1971; David and Lead, 1982; Millington, 2006a).

Fibres which have a hollow or a partially filled central canal running either as a continuous or in a fragmented form along their length are known as medullated fibres. Medullated fibres affect numerous properties of mohair textiles (Hunter, 1993). Because medullated fibres, and particularly kemp, tend to lie on the surface of the yarn and fabric, and are generally much thicker than the surrounding fibres, the visual and other effects they produce can be out of proportion to the actual quantity present. Furthermore, dyed medullated fibres generally appear much lighter than the surrounding dyed non-medullated fibres, and show up prominently in the fabric. This occurs as the medulla affects the optical properties of light passing through the fibre by diffraction, not from differences in dye uptake by the keratin of the fibre (Hirst and King, 1926; Hunter, 1993).

After accounting for other effects including MFD in the prediction models in the season study, increasing the incidence of Med increased Y to a greater extent than Z resulting in a significant increase on Y-Z. Over the range of Med in the samples of 0.3-4.2%, Y-Z increased by ≈ 11 T units (Fig. 4f). Previous reports on the effect of medullated fibres on tristimulus values of mohair or wool have not been located. This effect may be mediated by the reflection and scattering of light from interface between the keratin cells and the medulla within the mohair fibres.

These findings reinforce the view (McGregor and English, 2010) that mohair producers will maximize their financial rewards by maintaining a focus on the production of finer mohair with low levels of medullated fibre, as any potential price reduction on the basis of tristimulus values would penalize the coarser and more medullated mohair.

4.2. Effect of season, year and sire

Season affected mohair tristimulus values Y, Z and Y-Z. Autumn grown mohair had higher Y and Z and summer grown mohair had lower Z than mohair grown in other seasons. This resulted in summer grown mohair having the highest Y-Z and winter grown mohair having the lowest Y-Z than mohair grown in other seasons (Table 6). The differences between years in Y, Z and Y-Z were not large. The
differences detected between seasons are most likely to be related to the natural variation in solar
radiation given the seasonal change in the altitude of the sun (Godar, 2005) but variation in the intake
of natural plant chromophores and perhaps mineral intake may modify the effect of the natural rhythm
of solar radiation on tristimulus values to varying extents. These variations would be mediated by
differences in rainfall affecting pasture growth and variations in cloud cover influencing solar
radiation and together may explain the small differences detected in the tristimulus values between
years.

In the season study, knowledge of the genetic origin of the goats was a significant determinant of
the Y, Z and Y-Z of mohair. This appears to be a new finding as no other report of a genetic effect on
mohair reflectance traits has been located. Such an effect is not surprising as variation in genetic
origin affects the Y and Y-Z of wool and both attributes are moderately heritable (Wuliji et al., 2001;
Hatcher et al., 2010).

5. Conclusions

The extent of the differences in tristimulus values between seasons and years were not large and are
unlikely to be of commercial importance. However, the extent of the differences in tristimulus values
between farms, and related to variations in MFD and Med were large enough to be of commercial
importance. Any evaluation of the genetics of mohair colour properties needs to make appropriate
adjustments prior to determining genetic parameter estimates.

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7. References


Interscience, New York.


Table 1. For each farm, the State, climate zone, rainfall, the number and the mean clean mohair production for six months growing period for goats whose fleeces were tested for colour attributes.

<table>
<thead>
<tr>
<th>Farm</th>
<th>State</th>
<th>Climate zone</th>
<th>Rainfall (mm)</th>
<th>n</th>
<th>Greasy mohair production (kg/goat)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>South Australia</td>
<td>Wheat-sheep</td>
<td>251</td>
<td>46</td>
<td>2.60</td>
</tr>
<tr>
<td>5</td>
<td>Queensland</td>
<td>Wheat-sheep</td>
<td>591</td>
<td>29</td>
<td>1.80</td>
</tr>
<tr>
<td>7</td>
<td>Vic</td>
<td>Wheat-sheep</td>
<td>385</td>
<td>22</td>
<td>2.76</td>
</tr>
<tr>
<td>9</td>
<td>NSW</td>
<td>High rainfall</td>
<td>228</td>
<td>46</td>
<td>1.83</td>
</tr>
<tr>
<td>12</td>
<td>Vic</td>
<td>Wheat-sheep</td>
<td>200</td>
<td>53</td>
<td>1.88</td>
</tr>
</tbody>
</table>

Table 2. Mean, standard deviation (s.d.) and ranges in measured variables of white mohair originating from five farms (n = 196).

<table>
<thead>
<tr>
<th>Variables</th>
<th>Mean</th>
<th>s.d.</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age of goat (years)</td>
<td>2.5</td>
<td>1.32</td>
<td>0.5</td>
<td>4.5</td>
</tr>
<tr>
<td>Live weight at shearing (kg)</td>
<td>30.4</td>
<td>11.0</td>
<td>9.8</td>
<td>57.5</td>
</tr>
<tr>
<td>Greasy fleece weight (kg)</td>
<td>2.13</td>
<td>0.71</td>
<td>0.50</td>
<td>3.79</td>
</tr>
<tr>
<td>Clean washing yield (% w/w)</td>
<td>82.6</td>
<td>4.73</td>
<td>66.4</td>
<td>95.7</td>
</tr>
<tr>
<td>Staple length (cm)</td>
<td>11.0</td>
<td>2.1</td>
<td>6.0</td>
<td>16.5</td>
</tr>
<tr>
<td>Mean fibre diameter (μm)</td>
<td>29.8</td>
<td>4.81</td>
<td>19.0</td>
<td>41.2</td>
</tr>
<tr>
<td>Fibre diameter coefficient of variation (%)</td>
<td>26.3</td>
<td>3.86</td>
<td>17.6</td>
<td>43.2</td>
</tr>
<tr>
<td>Fibre curvature (°/mm)</td>
<td>14</td>
<td>2.4</td>
<td>9</td>
<td>22</td>
</tr>
<tr>
<td>Incidence of medullated fibres (% by number)</td>
<td>1.3</td>
<td>0.63</td>
<td>0.3</td>
<td>3.7</td>
</tr>
<tr>
<td>X (T units)</td>
<td>64.4</td>
<td>2.62</td>
<td>57.4</td>
<td>71.4</td>
</tr>
<tr>
<td>Y (T units)</td>
<td>68.0</td>
<td>2.78</td>
<td>60.4</td>
<td>75.5</td>
</tr>
<tr>
<td>Z (T units)</td>
<td>60.5</td>
<td>3.08</td>
<td>52.3</td>
<td>68.3</td>
</tr>
<tr>
<td>Y-Z (T units)</td>
<td>7.6</td>
<td>0.94</td>
<td>5.6</td>
<td>10.1</td>
</tr>
</tbody>
</table>
Table 3. The correlation coefficient ($r$) and $P$-value for significant terms in the models for mohair X, Y, Z and Y-Z with farm and other fibre attributes.

<table>
<thead>
<tr>
<th>Term</th>
<th>X</th>
<th>Y</th>
<th>Z</th>
<th>Y-Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>$r$</td>
<td>0.63</td>
<td>0.64</td>
<td>0.57</td>
<td>0.65</td>
</tr>
<tr>
<td>Constant</td>
<td>$&lt; 0.001$</td>
<td>$&lt; 0.001$</td>
<td>$&lt; 0.001$</td>
<td>$&lt; 0.001$</td>
</tr>
<tr>
<td>Farm</td>
<td>$1.5 \times 10^{-6}$</td>
<td>$2.7 \times 10^{-7}$</td>
<td>0.00035</td>
<td>$3.3 \times 10^{-24}$</td>
</tr>
<tr>
<td>Clean washing yield</td>
<td>$1.6 \times 10^{-5}$</td>
<td>$8.4 \times 10^{-6}$</td>
<td>$5.0 \times 10^{-5}$</td>
<td>-</td>
</tr>
<tr>
<td>CV fibre diameter</td>
<td>0.005</td>
<td>0.004</td>
<td>0.009</td>
<td>-</td>
</tr>
<tr>
<td>Staple length</td>
<td>0.019</td>
<td>0.013</td>
<td>0.034</td>
<td>-</td>
</tr>
<tr>
<td>Mean fibre diameter</td>
<td>0.024</td>
<td>0.032</td>
<td>0.0014</td>
<td>$1.8 \times 10^{-9}$</td>
</tr>
</tbody>
</table>

Table 4. Regression constants (s.e.) for relationships between white mohair tristimulus values X, Y, Z and Y-Z with farm and other fibre attributes. The constant is for farm 4

<table>
<thead>
<tr>
<th>Dependant variate</th>
<th>X</th>
<th>Y</th>
<th>Z</th>
<th>Y-Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>51.4 (3.92)</td>
<td>53.9 (4.09)</td>
<td>47.7 (4.87)</td>
<td>4.6 (0.37)</td>
</tr>
<tr>
<td>Farm</td>
<td>-0.2-3.9 (0.44-)</td>
<td>-0.5-4.2 (0.46-)</td>
<td>-1.6-2.9 (0.54-)</td>
<td>0.62-1.32 (0.15-)</td>
</tr>
<tr>
<td>Clean washing yield</td>
<td>0.17 (0.038)</td>
<td>0.18 (0.039)</td>
<td>0.19 (0.047)</td>
<td></td>
</tr>
<tr>
<td>CV fibre diameter</td>
<td>0.12 (0.044)</td>
<td>0.13 (0.046)</td>
<td>0.14 (0.054)</td>
<td></td>
</tr>
<tr>
<td>Staple length</td>
<td>-0.23 (0.100)</td>
<td>-0.26 (0.101)</td>
<td>-0.26 (0.121)</td>
<td></td>
</tr>
<tr>
<td>Mean fibre diameter</td>
<td>-0.09 (0.038)</td>
<td>-0.08 (0.039)</td>
<td>-0.15 (0.047)</td>
<td>0.08 (0.012)</td>
</tr>
</tbody>
</table>
Table 5. Mean, standard deviation (s.d.) and ranges in measured attributes of white mohair grown during three month growing seasons between February 2004 and February 2006 from Angora goats grazed at Attwood (pooled data, \( n = 176 \)).

<table>
<thead>
<tr>
<th>Variables</th>
<th>Mean</th>
<th>s.d.</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Live weight at shearing (kg)</td>
<td>36.2</td>
<td>8.45</td>
<td>16.8</td>
<td>57.5</td>
</tr>
<tr>
<td>Greasy fleece weight (kg)</td>
<td>1.23</td>
<td>0.39</td>
<td>0.50</td>
<td>2.34</td>
</tr>
<tr>
<td>Clean washing yield (% w/w)</td>
<td>85.9</td>
<td>5.42</td>
<td>67.0</td>
<td>96.7</td>
</tr>
<tr>
<td>Staple length (cm)</td>
<td>7.2</td>
<td>1.39</td>
<td>5.0</td>
<td>11.5</td>
</tr>
<tr>
<td>Mean fibre diameter (µm)</td>
<td>32.1</td>
<td>4.27</td>
<td>20.9</td>
<td>41.5</td>
</tr>
<tr>
<td>Fibre diameter coefficient of variation (%)</td>
<td>24.6</td>
<td>3.89</td>
<td>17.6</td>
<td>36.2</td>
</tr>
<tr>
<td>Fibre curvature (°/mm)</td>
<td>13</td>
<td>1.9</td>
<td>9</td>
<td>20</td>
</tr>
<tr>
<td>Incidence of medullated fibres (% by number)</td>
<td>1.7</td>
<td>0.85</td>
<td>0.3</td>
<td>4.2</td>
</tr>
<tr>
<td>X (T units)</td>
<td>66.3</td>
<td>2.66</td>
<td>56.2</td>
<td>72.2</td>
</tr>
<tr>
<td>Y (T units)</td>
<td>70.3</td>
<td>2.67</td>
<td>62.9</td>
<td>76.4</td>
</tr>
<tr>
<td>Z (T units)</td>
<td>62.1</td>
<td>3.07</td>
<td>51.6</td>
<td>68.1</td>
</tr>
<tr>
<td>Y-Z (T units)</td>
<td>8.0</td>
<td>0.96</td>
<td>5.5</td>
<td>10.5</td>
</tr>
</tbody>
</table>
Table 6. The effect of season on Y, Z and Y-Z of mohair from the mid-side site. The mohair was harvested from the Angora goats every three months over a 2-year period. Within parameters values with different superscripts differ at $P = 0.05$. Values are T units.

<table>
<thead>
<tr>
<th>Year</th>
<th>Autumn</th>
<th>Winter</th>
<th>Spring</th>
<th>Summer</th>
<th>l.s.d. 5%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$Y$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2004</td>
<td>72.97a</td>
<td>67.63cd</td>
<td>68.43c</td>
<td>67.26d</td>
<td>0.924</td>
</tr>
<tr>
<td>2005</td>
<td>72.57a</td>
<td>71.22b</td>
<td>70.85b</td>
<td>70.73b</td>
<td></td>
</tr>
<tr>
<td>Season mean</td>
<td>72.77a</td>
<td>69.43b</td>
<td>69.64b</td>
<td>69.00b</td>
<td>0.645</td>
</tr>
<tr>
<td>$Z$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2004</td>
<td>63.94b</td>
<td>60.06d</td>
<td>60.44d</td>
<td>58.57e</td>
<td>1.087</td>
</tr>
<tr>
<td>2005</td>
<td>65.27a</td>
<td>63.51b</td>
<td>63.02b</td>
<td>61.90c</td>
<td></td>
</tr>
<tr>
<td>Season mean</td>
<td>64.60a</td>
<td>61.79b</td>
<td>61.73b</td>
<td>60.23c</td>
<td>0.768</td>
</tr>
<tr>
<td>$Y-Z$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2004</td>
<td>9.03a</td>
<td>6.94c</td>
<td>7.99c</td>
<td>8.69b</td>
<td>0.337</td>
</tr>
<tr>
<td>2005</td>
<td>7.30d</td>
<td>7.71c</td>
<td>7.84c</td>
<td>8.84ab</td>
<td></td>
</tr>
<tr>
<td>Season mean</td>
<td>8.17b</td>
<td>7.33d</td>
<td>7.91c</td>
<td>8.76a</td>
<td>0.239</td>
</tr>
</tbody>
</table>
Figure Captions

Fig. 1. Box plots showing the mean (horizontal line) and range in (a) the Y and (b) Y-Z of mohair originating from different farms without adjustment for any other effect. Values are T units.

Fig. 2. The relationship between the tristimulus values a) X, b) Y, c) Z and d) Y-Z and mohair mean fibre diameter after adjustment for farm and any other significant terms in the model. Values are T units.

Fig. 3. The relationship between the Y of mohair and a) clean washing yield, b) coefficient of variation of fibre diameter, and c) mohair staple length, after adjustment for the farm effect and other terms in the model. Higher Y increases brightness. Values are T units.

Fig. 4. The relationship between the tristimulus values Y (a and d), Z (b and e) and Y-Z (c and f) of mohair grown in each season and mohair mean fibre diameter (µm; a, b, c) or the incidence of medullated fibres (%, by number; d, e, f) after adjustment for farm and any other significant terms in the model. Symbols: autumn, □, solid line; winter, ▲, dash line; spring, ▽, dash dot dash line; summer, ●, dotted line. Values are T units.