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The allometric relationship between mean fibre diameter of mohair and the fleece-free live weight of Angora goats over their lifetime

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Short title: Lifetime changes in mohair fibre diameter

Abstract.

As mean fibre diameter (MFD) is the primary determinant of mohair price we aimed to quantify the lifetime changes in mohair MFD as Angora goats aged and grew. Measurements were made over 12 shearing periods on a population of Angora goats representing the current range and diversity of genetic origins including South African, Texan and interbred admixtures of these and Australian sources. Records of sire, dam, birth weight, birth parity, live weight, fleece growth and fleece quality were taken for does and castrated males (wethers) (*n*=267 animals). Fleece-free liveweights (FFLwt) were determined for each goat at shearing time by subtracting the greasy fleece weight from the live weight recorded immediately prior to shearing. A restricted maximum likelihood (REML) growth curve model was developed for relating MFD to FFLwt, age and other measurements. A simple way of describing the results is: MFD = κ (FFLwt)$^{\beta}$ E; where κ is a parameter that can vary in a systematic way with shearing(age), breed, weaning weight, sire, dam and individual; β is a parameter that is the same for nearly the whole study; and E are independent errors from a log-normal distribution. The analysis shows that $\hat{\beta}$ = 0.34, with s.e. ($\hat{\beta}$) = 0.021. Thus, mohair MFD was allometrically related to the cube root of FFLwt over the lifetime of Angora goats. However the allometric proportionality constant differed in a systematic way with age at shearing, genetic strain, weaning weight, sire, dam and individual. For Texan-breed goats, MFD decreased as weaning weight increased (P = 0.00016). The findings indicate that management factors which affect liveweight and weaning weight have lifetime effects on mohair fibre diameter and therefore the value of mohair and the profitability of the mohair enterprise.

Additional keywords: age effects, genotype, mohair production, nutritional management, weaning management.

Introduction

In the nineteenth century the Australian mohair industry was established on imported South African Angora goat genetics (Balasingham *et al*. 1999). In recent decades the Australian mohair industry has a strong record of genetic importation. In an attempt to increase mohair production, reduce the incidence of medullated fibres and improve fleece style and character, Australian investors imported Texan (1984) and South African (1990) strains of Angora goats. Progeny of Texan and Texan × Australian Angora goats were released from quarantine in 1992 (McGregor 1992*a*). Since this time mohair producers interbred the new genotypes with the older Australian genotypes or maintained the imported stains (Ferguson and McGregor 2004, 2005; Stapleton and Cunningham 2007).

Mean fibre diameter (MFD) is the primary determinant of mohair price, accounting for near 60% of the variation in price (McGregor and Butler 2004). Between 1998 and 2002 maximum prices were received for mohair of 24-25 µm with discounts of 50% for mohair of MFD 30 µm and 90% for mohair of MFD of 36 µm. The year effect on premiums or discounts varied for coarser mohair but at no time did it remove the significant premium for 24-25 µm fibre. Thus efforts to improve the quality and financial returns from mohair production need to primarily focus on mohair MFD. Recently, mohair enterprise benchmarking conducted over 3 years showed that income from mohair sales declined as the proportion of does in the flock increased. Increasing the proportion of does in the flock was associated with a decline in the average price of mohair ($16/kg greasy at 42% does to $8/kg greasy at 83% does in the flock). This decline was closely associated with the increasing proportion of the total amount of mohair coarser than 34.0 µm plus stained mohair (McGregor and English 2010). However it is unknown to what extent that the increase in the proportion of coarser Australian mohair is related to age effects, live weight effects, genetic or reproductive effects and so many mohair producers may not be in a position to clearly manage the changes in mohair MFD.

In the absence of objective information about life time changes in mohair MFD as modern Australian Angora goats age and grow, we investigated the relationship between mohair MFD and age, live weight and other lifetime factors on a population of Angora goats representing the current range and diversity of genetic origins in Australia.

Materials and methods

General

Most management details have been provided by McGregor and Butler (2008). In brief, Angora goats born in September 2002 in a progeny testing evaluation at Horsham, Victoria, (36º42'50"S, 142º18'30"E, altitude 180 m) with pedigree breeding records from known sires, were grazed on pasture from birth until 6 years of age. The goats were progeny of various genetic sources including sires of 100% South African origin (*n* = 2), 100% Texan origin (*n* = 4), and other interbred admixtures that included sires of South African, Texan and Australian origin (*n* = 4). These sires were representative of the genotypes available in Australia (Ferguson and McGregor 2004, 2005). Records of dam, birth weight, birth parity, live weight, fleece growth and fleece quality were taken for does and castrated males (wethers). All animals were shorn every 6 months from 6 months of age, except as described below. One month after shearing in February 2004 the wether goats were transported to Attwood, Victoria (37°40’S, 144°53’E, altitude 135 m) and grazed as a flock until November 2008.

Management

Goats were grazed as one flock, at near the recommended stocking rate on improved annual pasture (McGregor 2010). Goats were moved between paddocks to match feed requirements. Shelter was available in the form of covered and enclosed shedding that was always accessible and could accommodate all goats. Fresh water was provided in all paddocks. During most years in autumn and winter, pastoral conditions were affected by drought and supplementary feeding was undertaken following Australian practice (McGregor 2005) from mid May to early September to maintain live weight (McGregor and Butler 2008). A mineralised stock block was always available (Ridley AgriProducts Pty. Ltd., Melbourne) with the following content: Minimum content Ca 4.9%; P 1%; S

2%; Cu 600 mg/kg; Co 60 mg/kg; I 60 mg/kg; Zn 1000 mg/kg; Fe^{+2} 1100 mg/kg; Se 5 mg/kg; based on NaCl 75 to 85%.

The goats were given a full crutching and wigging three months prior to any shearing. Goats were vaccinated against 5 in 1 *Clostridia spp*. and "drenched" with an effective anthelmintic to control gastro-intestinal parasites no more frequently than once per year. All goats were weighed to the nearest 0.2 kg one day prior to any shearing except for the third shearing when the nearest live weight prior to shearing was taken three months earlier at 15 months of age and following shearing one month later. All goats were fasted overnight prior to shearing or crutching. Goats were returned to pasture together following shearing.

Design

The goats studied were the progeny of a sire evaluation project (Ferguson and McGregor 2004, 2005). Between February 2004 and February 2006 the goats were part of a replicated experiment studying the influence of shearing treatments. There were four or eight individual goat replicates of 21 treatments arranged as a 7 Shearing treatments by 3 Genetic strains factorial (McGregor and Butler 2008). The shearing treatments were:

- Three different six month shearing intervals, each with different months of shearing: February-August, April-October, June-December;
- Two 12 months shearing intervals with different months of shearing: August-August, September-September;
- One 3 month shearing interval (Often treatment); and
- One seven-month winter shearing interval, February-September.

Genetic strain was based on sire line as follows:

- South African: Sires 100% South African bloodline;
- Texan: Sires 100% Texan bloodline; and

- Mixed: Sires of approximately 50% South African and 50% Texan bloodlines.

Some strains of wethers, whose breeding did not fit within these criteria, were culled.

Mohair testing

The practices were exactly as previously described (McGregor and Butler 2008). At crutching and shearing, fleeces, pieces, bellies and locks and samples were weighed to the nearest 1 g. Mid-side samples were taken at shearing, identified and stored in a plastic bag. The mid-side samples were then mini-cored and tested by OFDA100 for mean fibre diameter (IWTO 2005).

Statistical methods

Fleece-free live weights (FFLwt) were determined for each goat at shearing time by subtracting the greasy fleece weight from the live weight recorded immediately prior to shearing. A parsimonious restricted maximum likelihood (REML) growth curve model, as enacted by GENSTAT 13.1 (Payne 2010), was developed for MFD after $\log_{10}$ transformation. Separate terms were developed for fixed effects, random individual goat effects, random sire effects and random dam effects. REML enables the inclusion into the model of random effects and variates and provides the statistical evidence for their retention and quantification of their effect. Base models were developed to account for background sources of variation, using Chi-square change in deviance tests for random effects and Wald *F*-tests for fixed effects (Payne 2010). In the results the symbol, *, represents a crossing operator, and the symbol, /, represents a nesting operator.

Results

Although date of birth only differed by 20 days, a wide range of dam age, parity, birth and weaning weight were observed (Table 1). The trend for MFD was to increase until 2.5 years of age, and then fluctuate from shearing to shearing (Fig. 1*a*). The general trend for FFLwt was to increase with shearing age, although there was substantial year to year fluctuation (Fig. 1*b*). Nevertheless there was considerable variation in both MFD and FFLwt within each shearing (Fig. 1).

In addition to a random error, the parsimonious growth curve model for the logarithm of MFD has four types of terms. These were a) fixed effects, b) random individual goat effects, c) random sire effects and d) random dam effects (Table 2). The four types of random effects were mutually independent. The fixed effects in the model for the logarithm of MFD can be represented as (Table 2, 3*a*):

$$Log_{10}(MFD) = Shearyears*Shearregime + Breed*Weaningwt + Age1pt5*LogAdjLwt + Age1pt5/(DOBin1pt5 + Birthwtin1pt5) + Age;$$

The random individual goat effects can be represented as (Table 2, 3*b*, 4):

$$Log10(MFD) = \alpha + \beta_1 Agevarlt5 + \beta_2 Seasonvar + \beta_3 (Agevarlt5 \times Seasonvar) + \beta_4 Agevarlinabove5;$$

where α, β_1, β_2, β_3, β_4 are correlated random variables across individual goats.

The random sire effects can be represented as (Table 2, 3*c*, 4):

$$Log10(MFD) = \alpha + \beta_1 Agevarlt5 + \beta_2 Seasonvar;$$

where α, β_1, β_2 are correlated random variables across individual sires.

The random dam effects can be represented as (Table 3d, 4) for each individual dam:

$$Log10(MFD) = \alpha;$$

where α is a random variable across individual dams.

A good deal of the complexity of the fixed effect component of the parsimonious model is specific to explaining variation at the 1.5-year shearing. If the 1.5-years shearing is excluded, then the fixed effect component of the model simplifies to:

$$Log_{10}(MFD) = Breed*Weaningwt + LogAdjLwt + Age.$$

We suggest that the complexity involved with the 1.5-year shearing is likely to be due to measurement issues (see Discussion), and thus it will be excluded from the remainder of the results.

For the remainder of the shearings, a simple way of describing the results is:

$$MFD = \kappa (FFLwt)^{\beta} E;$$

where κ is a parameter that can vary in a systematic way with shearing(age), breed, weaning weight, sire, dam and individual;

β is a parameter that is the same for the whole study (excluding shearing age of 1.5 years); and

E are independent errors from a log-normal distribution.

The analysis shows that $\hat{\beta}$ = 0.34, with s.e. ($\hat{\beta}$) = 0.021. Thus, MFD is proportional to the cube root of FFLwt, although the constant of proportionality will change in a systematic way with shearing(age) (Fig. 2), as well as breed, weaning weight, sire, dam and individual. For Texan breed goats, MFD decreased as weaning weight increased (Fig. 3).

There is a substantial variation in MFD that is not accounted by the fixed effects of FFLwt, age, breed and weaning weight, and this variation increases moderately with age (Figure 4). For instance, in situations where MFD is predicted to be 30 µm, the 95% quantile range of MFD increases from 11 µm at 1.5 years to 14 µm at 6 years of age.

The contribution of the random variation due to systematic animal (including sire and dam) effects is best summarized on the logarithmic scale as, $\left(\frac{\sigma^2_{Sire} + \sigma^2_{Dam} + \sigma^2_{Animal}}{\sigma^2_{Sire} + \sigma^2_{Dam} + \sigma^2_{Animal} + \sigma^2_{error}} \right)$. This can, equivalently, be interpreted as the proportion of total random variance of the logarithm of κ that is associated with systematic animal effects. Table 5 shows that the proportion of total random variance of the logarithm of κ that is associated with systematic animal effects increases from about 80 to 90 per cent as the age of goat increases from 1 year old to 6 years old. The proportion is somewhat greater at autumn shearings (i.e. 2.5, 3.5…. years old).

The correlation of the random effects of the logarithm of κ systematically associated with animal ($\sigma^2_{Sire} + \sigma^2_{Dam} + \sigma^2_{Animal}$) between different shearing ages is given in Table 6. This shows that at any shearing age the correlations are highest (0.94-0.97) between that shearing and the shearing one year later. Generally, correlations then decline with increasing shearing age, particularly for shearing ages 1 and 2 years. The correlations for shearing age 1 and shearing ages > 4 years were ≤ 0.40 but at shearing ages ≥ 2.5 years the correlations at any older age were ≥ 0.65.

Discussion

The life time change in mohair MFD was proportional to the cube root of the FFLwt of Angora goats and this was true for three Angora goat genotypes. Variation in weaning weight in one genotype of Angora goat was also a determinant of lifetime mohair fibre diameter. Age *per se* was not a substantial determinant of mohair fibre diameter, once fleece-free live weight was taken in to account.

Influence of fleece-free live weight

The results indicate that there is an allometric relationship between mohair fibre diameter and the fleece-free live weight of Angora goats. To the extent that shorn fibres of different sizes are geometrically similar (i.e. the three-dimensional shape does not change as the shorn fibre size increases) the volume of a shorn fibre will be proportional to the cube of the fibre diameter (i.e. fibre diameter × fibre diameter × fibre diameter). Further, to the extent that the density (mass to volume) of shorn fibres does not change as fibres increase in size (something expected when medullation is low), the weight of a shorn fibre will be proportional to the volume of a fibre. Thus, as the number of fibres produced by an Angora goat is determined by the number of fibre follicles produced pre- and post natally (Margolena 1974), it is reasonable that the total weight of shorn fibres is proportional to the cube of fibre diameter. Furthermore, to the extent that the proportion of resources used for fibre production by a non-breeding goat remains constant as the size of a goat increases (SCA 1990), then the total weight of shorn fibre is likely to be proportional to the FFLwt. Putting all this together, it is not unreasonable that FFLwt is proportional to the cube of fibre diameter, or equivalently fibre diameter is proportional to the cube root of FFLwt. This is exactly what we found.

Such allometric relationships are common in animal production, and elsewhere in biology (Schmidt-Nielsen 1984). For Australian grazing goats, as with other animals, the growth of the carcass, fat deposits and various organs are allometrically related to liveweight (McGregor 1982, 1992*b*). The metabolic activity of goats and other mammals is related to liveweight$^{0.75}$ (Armstrong and Blaxter 1965; SCA 1990), gut content of herbivores is related to liveweight$^{1.03}$ (Demment and Van Soest 1985), the breadth of the incisor arcade to the liveweight$^{0.29}$ of sheep (Taylor *et al*. 1987), lifespan of mammals in captivity is related to liveweight$^{0.20}$ (Schmidt-Nielsen 1984), and length based attributes, including wing length of birds, change with liveweight$^{0.33}$ (Schmidt-Nielsen 1984; Niklas 1994; Damuth 2001). In deer, antler length is related to body mass but is influenced by breeding group size and male-male competition (Plard *et al*. 2011). Silva (1998) concluded that in mammals, body mass was highly allometrically related with body length whether mammals were grouped by locomotion or taxon.

A phenotypic relationship between mohair MFD and live weight has been reported in previous studies of Angora goats from South Africa, Texas, Turkey, Australia and New Zealand (Shelton and Bassett 1970; Yalcin *et al*. 1979; Nicoll *et al*. 1989; Gifford *et al*. 1991; Snyman and Olivier 1996; McGregor 2010). Wool fibre diameter is also phenotypically positively related to live weight of Merino sheep (Huisman and Brown 2008). Across 268 Merino bloodlines (genotypes), Martin *et al*. (2010) reported that for each 1 µm increase in MFD liveweight increased 1.2%.

With fibre producing animals follicle initiation is completed by about 4 months of age resulting in increases in liveweight from this age being correlated with reductions in the density of fibre producing follicles and the growth of coarser fibres (Fraser and Short 1960; Maddocks and Jackson 1988; Eppleston and Moore 1990; Scobie and Young 2000; Adams and Cronjé 2003; Toland Thompson *et al.* 2007). It has generally been accepted that the mechanism for this relationship is that reduced density of skin follicles leads to less competition between follicles, thus increasing both follicle bulb dimensions and nutrient supply to each follicle (Hynd 1994). The results of the present study give an alternative explanation, namely that the dimension of fibres is directly in line with the size of the animal through an allometric relationship.

At the third shearing (1.5 years old) the coefficient of the logarithm_{10} of liveweight (0.18, se = 0.032) was different to the coefficient obtained at other ages ($P = 6 \times 10^{-7}$), and there were also effects of birth weight and day of birth. We suggest that these effects are artefacts of no reliable pre-shearing live weight. For all other shearings a liveweight was taken within two days of shearing. For the third shearing the nearest liveweight prior to shearing was taken three months earlier at 15 months of age and following shearing one month later. During this time period the goats experience drought and liveweight loss averaging 1 kg but varying from -7 to + 7 kg between goats. Following their third shearing the goats were also transferred to the research farm over a distance > 300 km.

Effect of weaning weight, dam age and birth type on MFD

Lower weaning weight of Texan Angora goats was associated with coarser mohair MFD for the lifetime of the Angora goats. With the sires of Texan origin we examined, kids weaned at low liveweights produced mohair up to 8 µm coarser than heavier kids (Fig. 3). Such large differences in MFD would result in a substantial discount in the value of mohair (McGregor and Butler 2004). For example, increasing MFD from 28 to 32 µm is associated with a discount of 45% and such a change in MFD is equivalent to the difference between weaning weights of 12 and 20 kg (Fig. 3). It is highly likely that the effect of weaning weight on MFD is related to the development of secondary fibre follicles in Angora goats. Previous work has demonstrated that improved nutritional management of Angora does is associated with greater skin follicle density and the production of finer mohair by their kids as adults (McGregor 1995). Together these findings show that a greater focus on the nutrition of breeding does and kids to increase weaning weights will result in finer mohair for the lifetime of the goats and increased commercial value of the mohair and these effects may be greater in some genotypes.

Neither birthweight, dam age nor single births versus multiple births were significant once other terms in the model had been accounted for (Table 2). On farms, the main effect of these factors is to alter weaning weight e.g. Corner *et al.* (2008).

Random variation

While some of the fixed effects are very large, there is still a large amount of variation of MFD that is not accounted for by systematic fixed effects (Fig. 4). Of this random variation, most is from systematic effects of individual goats, rather than ephemeral or sampling effects (Table 5). Thus, the allometric coefficient relating mean fibre diameter to FFLwt has a large component that differs systematically with individuals.

The component of the allometric coefficient due to systematic effects of individual goats increases considerably with age and is somewhat greater in autumn. This greater proportion in autumn could be related to improved nutrition during late spring and early summer, and optimal photoperiod, allowing fibre producing follicles to express their fibre growth potential.

The correlation of systematic effects associated with animal declines to levels < 0.50 between ages ≤ 2 years and the oldest ages. This could indicate that ranking of animals in their efficiency of producing fibre from each follicle can change substantially as the goats become older.

Also correlations of systematic animal effects are greater for shearings taken at the same time of year. This can most easily be seen by noting that the correlations between ages 1 year apart (0.94-0.97) are greater than the correlations between ages 6 months apart (0.81-0.91) (Table 6). Thus the ranking of animals in their efficiency of producing fibre from each follicle can be considerably different for spring shearings than autumn shearings. This suggests that culling of animals should be based on mean fibre diameter obtained both from autumn and spring shearings, although between animal variation in the effect of season on liveweight growth also needs to be considered. This would be a worthwhile topic for further study.

Conclusion

Mean fibre diameter of mohair is allometricaly related to the cube root of liveweight, over the lifetime of Angora goats. However the allometric proportionality constant differs in a systematic way with age at shearing, genetic strain, weaning weight and individual. As the number of fibre follicles of an animal is determined at an early age, changes in the allometric proportionality constant with age might be an indicator of changes in the efficiency of fibre production of the follicle population. The findings indicate that management factors which affect liveweight and weaning weight have lifetime effects on mohair fibre diameter and therefore the value of mohair and the profitability of the mohair enterprise.

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References

Adams NR, Cronjé PB (2003) A review of the biology linking fibre diameter with fleece weight, liveweight, and reproduction in Merino sheep. *Australian Journal of Agricultural Research* **54**, 1-10.

Armstrong DG, Blaxter KL (1965) Effects of acetic and propionic acids on energy retention and milk secretion in goats. In "Energy Metabolism", (Ed. Baxter, KL), pp59-72 (Academic Press: London).

Balasingham TG, Robinson RA, McGregor BA (1999) Implications for the conservation of genetic diversity in mohair goats from a comparison of a relic island population with breeds farmed in Australia. *Australian Journal of Experimental Agriculture* **39**, 411 – 418, doi:10.1071/EA98061

Corner RA, Kenyon PR, Stafford KJ, West DM, Lopez-Villalobos N, Morris ST, Oliver MH (2008) Effect of nutrition from mid to late pregnancy on the performance of twin- and triplet- bearing ewes and their lambs. *Australian Journal of Experimental Agriculture* **48**, 666-671.

Damuth J (2001) Scaling of growth: plants and animals are not so different. *Proceedings of the National Academy of Sciences of the United States of America* **98**, 2113-2114.

Demment MW, Van Soest PJ (1985) A nutritional explanation for body-size patterns of ruminant and nonruminant herbivores. *American Naturalist* **125**, 641-672.

Eppleston J, Moore NW (1990) Fleece and skin characteristics of selected Australian Angora goats. *Small Ruminant Research* **3**, 397-402.

Ferguson MB, McGregor BA (2004) An evaluation of Angora sires through progeny testing- A progress report. *South African Journal of Animal Science* **34** (5), 7-9, http://www.sasas.co.za/journal/843

Ferguson MB, McGregor BA (2005) 'Selecting high performing Angoras'. RIRDC Research Report No 05/141. (Rural Industries Research and Development Corporation: Barton, ACT). https://rirdc.infoservices.com.au/items/05-141 [Verified 12 April 2011]

Fraser AS, Short BF (1960) *The Biology of the Fleece*. Animal Research Laboratories Technical Paper No. 3. (CSIRO: Melbourne)

Gifford DR, Ponzoni RW, Lampe RJ, Burr J (1991) Phenotypic and genetic parameters of fleece traits and live weight in South Australian Angora goats. *Small Ruminant Research* **4**, 293-302.

Huisman AE, Brown DJ (2008) Genetic parameters for bodyweight, wool, and disease resistance and reproduction traits in Merino sheep. 2. Genetic relationships between bodyweight traits and other traits. *Australian Journal of Experimental Agriculture* **48**, 11186-1193.

Hynd PI (1994) Follicular determinants of the length and diameter of wool fibres. 1. Comparison of sheep differing in fibre length/diameter ratio at two different levels of nutrition. *Australian Journal of Agricultural Research* **45**, 1137–1147.

IWTO (2005) ‘Measurement of the mean and distribution of fibre diameter of wool using an optical fibre diameter analyser (OFDA).’ IWTO-47. (International Wool Textile Organisation: Ilkley, UK)

Maddocks IG, Jackson N (1988) *Structural Studies of Sheep, Cattle and Goat Skin*. (CSIRO: Blacktown, NSW).

Margolena LA (1974) Mohair histogenesis, maturation and shedding in the Angora goat. Technical Bulletin 1945. (United States Department of Agriculture: Washington)

Martin SJ, Atkins KD, Semple SJ, Sladek MA, Thackeray RH, Staines JM, Casey AE, Graham RP, Russell AJ (2010) Merino bloodlines: the comparisons 1999-2010. Primefact 930. (Department of Industry & Investment NSW: Sydney)

McGregor BA (1982) Growth of organ and body components of grazing goats. *Proceedings of the Australian Society of Animal Production* **14**, 487-490.

McGregor BA (1992*a*) Advances in the production of high quality Australian mohair. In: McGregor, B.A. "Specialist Fibre Production and Marketing". *Proceedings of the Australian Society of Animal Production* **19**, 255-257.

McGregor BA (1992*b*) Body composition, body condition scores and carcass and organ components of grazing Angora goats. *Proceedings of the Australian Society of Animal Production* **19**, 273-276.

McGregor BA (1995). ‘Improving kid survival and mohair quality by improved nutritional management of reproducing does.’ Final Report RIRDC Project DAV 42A. (Agriculture Victoria: Attwood)

McGregor BA (2005) ‘Nutrition and management of goats in drought.’ Research Report No 05/188. (Rural Industries Research and Development Corporation: Barton, ACT). https://rirdc.infoservices.com.au/items/05-188 [Verified 12 April 2011]

McGregor BA (2010) The influence of stocking rate and mixed grazing of Angora goats and Merino sheep on animal and pasture production in southern Australia. 3. Mohair and wool production and quality. *Animal Production Science* **50**, 168-176, doi:10.1071/AN09186.

McGregor BA, Butler KL (2004) Contribution of objective and subjective attributes to the variation in commercial value of Australian mohair: Implications for mohair production, genetic improvement, and mohair marketing. *Australian Journal of Agricultural Research* **55**, 1283-1298, doi: 10.1071/AR04107

McGregor BA, Butler KL (2008) The effect of frequency and timing of shearing on the growth of fibre and objective and subjective attributes of Angora goat fleeces. *Journal of Agricultural Science, Cambridge* **146**, 351-361, doi: 10.1017/S0021859607007599

McGregor BA, English WD (2010). Gross margins in Australian mohair enterprises and relationships with farm inputs, productivity and mohair quality. *Animal Production Science* **50**, 573–580, doi: 10.1071/AN09224.

Nicoll GB, Bigham ML, Alderton MJ (1989) Estimates of environmental effects and genetic parameters for live weights and fleece traits of Angora goats. *Proceedings of the New Zealand Society of Animal Production* **49**, 183-189.

Niklas KJ (1994) The scaling of plant and animal body-mass, length, and diameter. *Evolution* **48**, 44-54.

Payne RW (Ed.) (2010) 'The Guide to GenStat®; Release 13. Part 2: Statistics.' (VSN International: Hertfordshire, UK)

Plard F, Bonenfant C, Gaillard JM (2011) Revisiting the allometry of antlers among deer species: male-male sexual competition as a driver. *Oikos* **120**, 601-606.

SCA (1990) Feeding Standards for Australian Livestock: Ruminants. (Standing Committee on Agriculture, CSIRO: East Melbourne)

Schmidt-Nielsen K (1984) 'Scaling: why is animal size so important?' (Cambridge University Press: Cambridge, UK)

Scobie DR, Young SR (2000) The relationship between wool follicle density and fibre diameter is curvilinear. *Proceedings of the New Zealand Society of Animal Production* **60**, 162-165.

Shelton M, Bassett JW (1970) 'Estimate of certain genetic parameters relating to Angora goats.' Texas Agricultural Station Research Reports (PR-2750), 38-41. (Texas Agricultural and Mechanical University: College Station, Texas)

Silva M (1998) Allometric scaling of body length: elastic or geometric similarity in mammalian design. *Journal of Mammalogists* **79**, 20-32.

Snyman MA, Olivier JJ (1996) Genetic parameters for body weight, fleece weight and fibre diameter in South African Angora goats. *Livestock Production Science* **47**, 1-6.

Stapleton DL, Cunningham DG (2007) 'Australian Handbook of Angora Goats and Mohair Production.' (Australian Goat Report: Grenfell, New South Wales, Australia)

Taylor StCS, Murray JI, Illius AW (1987) Relative growth of incisor arcade breadth and eating rate in cattle and sheep. *Animal Production* **45**, 453-458.

Toland Thompson AC, Hebart ML, Penno NM, Hynd PI (2007). Perinatal wool follicle attrition coincides with elevated perinatal circulating cortisol concentration in Merino sheep. *Australian Journal of Agricultural Research* **58**, 748-752.

Yalcin BC, Ariturk E, Imeryuz F, Sincer N, Muftuoglu, S. (1979). Genetic and environmental aspects of Angora goat production. 2. Phenotypic and genetic parameters for the important production traits. *Instanbul University Vet. Fak. Derg.* **5**, 19-34.

Figure captions

Fig. 1. Boxplots of (a) mean fibre diameter (μm) and (b) fleece-free liveweight at each shearing age. The boxes represent inter-quartile range and the whiskers represent 95% quantile range.

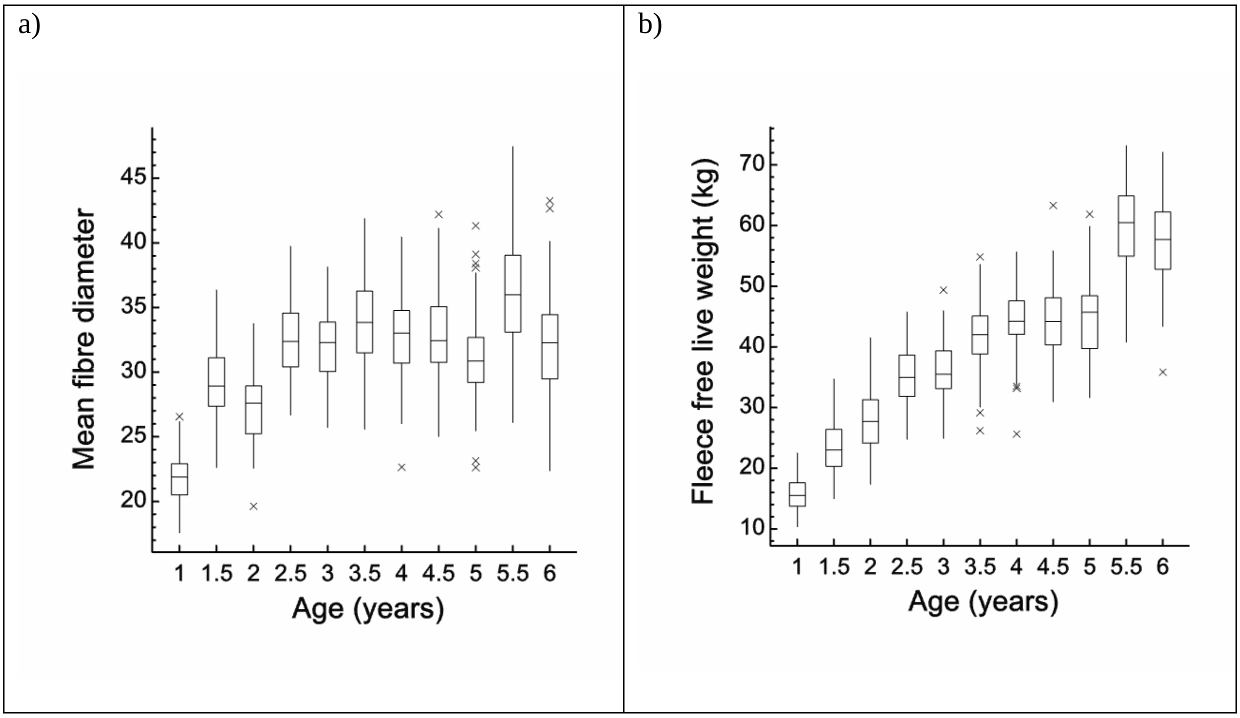

Fig. 2. Relationship between mohair mean fibre diameter, adjusted for other terms in the model on the logarithmic scale, and fleece-free liveweight at different ages. For 2- year- old to 3.5- year -old shearings the responses are shown for goats on the February/August shearing regime. Symbols: □, 1- year- old; ▲, 2- year- old; ■, 2.5- year- old; +, 3- year- old; △, 3.5- year- old; ×, 4- year- old; ◇, 4.5- year- old; ○, 5- year- old; ●, 5.5- year- old; ◆, 6- year-old.

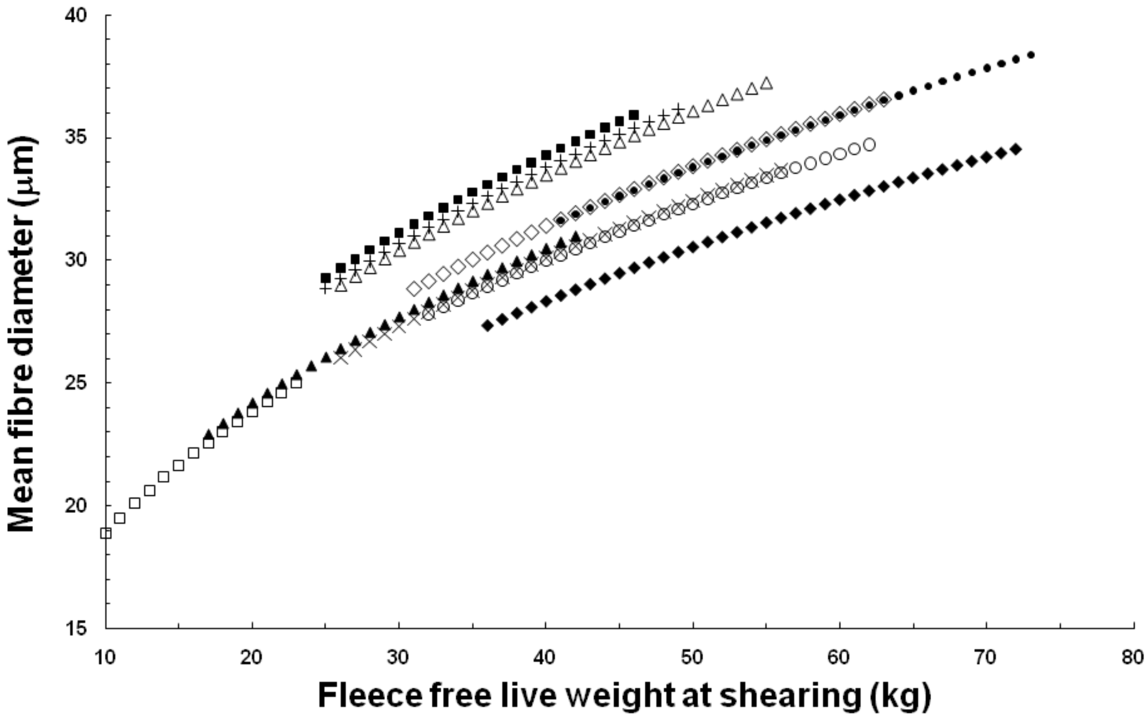

Fig. 3. Relationship between mohair mean fibre diameter, adjusted for other terms in the model on the logarithmic scale, and weaning weight of different breeds for 45 kg goats at the 4-year-old shearing. Response to weaning weight, Texan *P* = 0.00016; South African *P* = 0.13; Mixed *P* = 0.49. Symbols: □, South African; ▲, Texan; ●, Mixed breed.

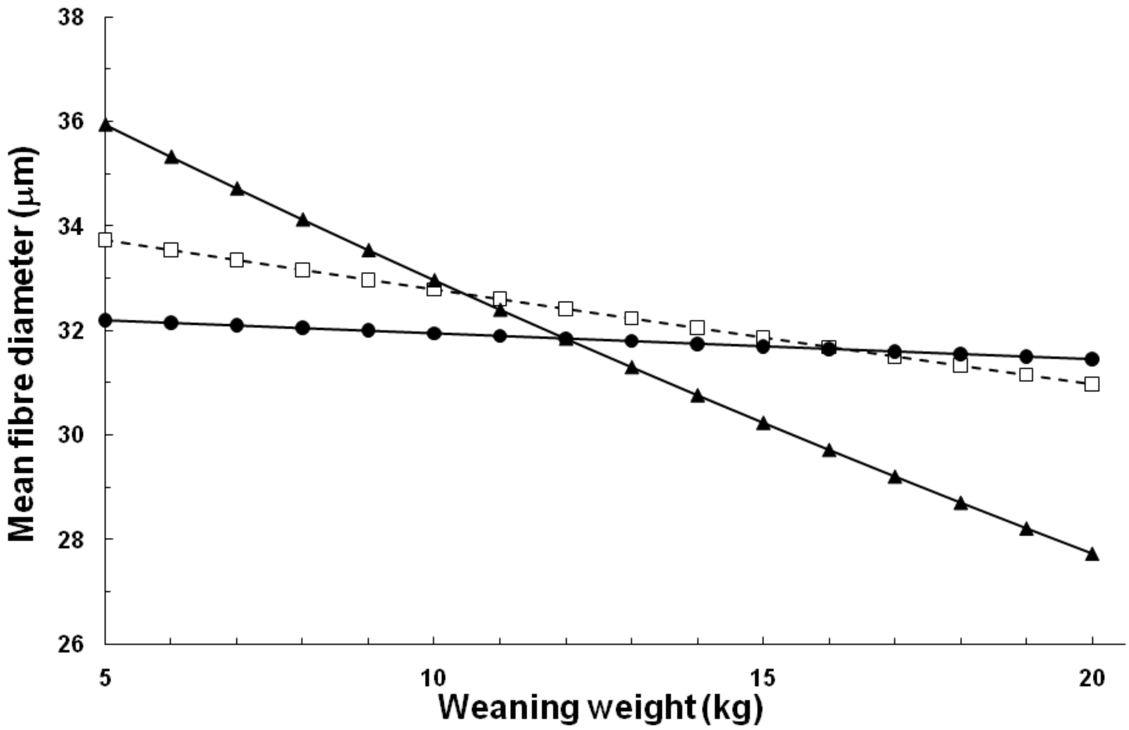

Fig. 4. Estimated variation in mean fibre diameter (μm) at each age when the predicted response to fixed effects is (*a*) 25 μm, (*b*) 30 μm and (*c*) 35 μm. The boxes represent inter-quartile range and the whiskers represent 95% quantile range. Results are only presented for combinations of age and predicted response that are represented in the study.

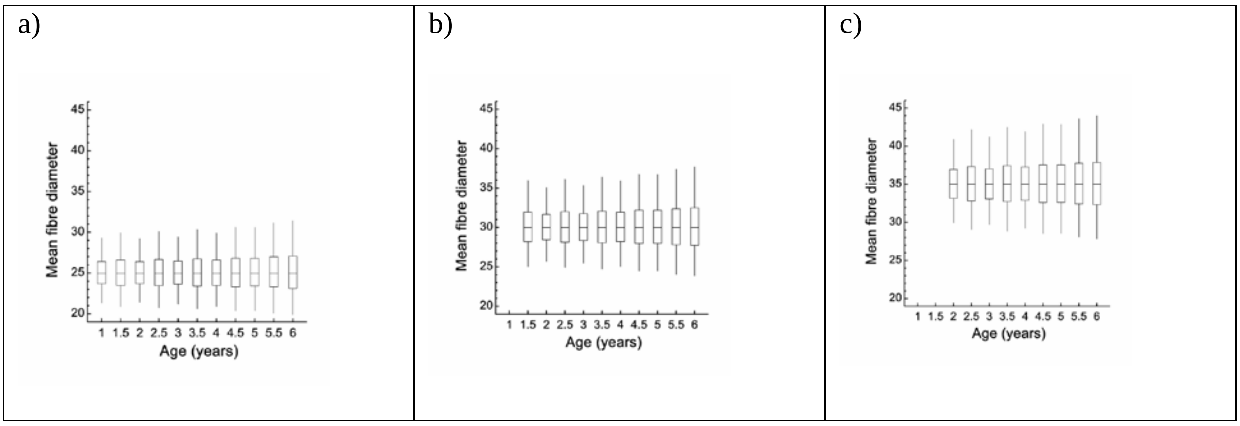

Table 1. Mean, standard deviation (s.d.) and range in one-off measurements of sampled Angora goats

Variables	Mean	s.d.	Minimum	Maximum	*n*
Date of birth (day of year)	254	4.1	243	263	240
Dam age at birth (years)	5	1.8	1	12	240
Mean parity (single =1; twin = 2; etc)	1.9	0.69	1	4	240
Birth weight (kg)	2.65	0.54	1.46	4.21	267
Weaning liveweight (kg)	11.5	3.43	4	20.5	267

Table 2. Terms in parsimonious growth curve model for the log_{10}(mean fibre diameter, MFD)

Acronym	Factor/Variate	Number of levels	Description
			Fixed effect terms
Shearyears	Factor	5	4 if MFD measured at 2 - year - old shearing 5 if MFD measured at 2½ - year - old shearing 6 if MFD measured at 3 - year - old shearing 7 if MFD measured at 3½ - year - old shearing NA otherwise
Shearregime	Factor	8	FebAug if animal was in February and August shearing regime and measured in Shearyears 4 to 7 FebSept if animal was in February and September shearing regime and measured in Shearyears 4 to 7 AprOct if animal was in April and October shearing regime and measured in Shearyears 4 to 7 JunDec if animal was in June and December shearing regime and measured in Shearyears 4 to 7 AugAug if animal was in August and August shearing regime and measured in Shearyears 4 to 7 SeptSept if animal was in September and September shearing regime and measured in Shearyears 4 to 7 Often if animal was in every 3 months shearing regime and measured in Shearyears 4 to 7 NA if measurement taken in other Shearyears
Breed	Factor	3	Texan, South African or mixed
Age1pt5	Factor	2	Indicator of whether measurement taken at 1.5 year old
logAdjLwt	Variate	Not applicable	log_{10} (liveweight prior to shearing - greasy fleece weight)
DOB1pt5	Factor	18	Indicates day of birth when measurement taken at 1.5 years old. Takes 'NA' level otherwise.
Birthwtin1pt5	Variate	Not applicable	Is birth weight when measurement taken at 1.5 years old. Takes value of 0 otherwise.
Age	Factor	11	Age (years) at shearing (1, 1.5, 2, 2.5, 3, 3.5, 4, 4.5, 5, 5.5, 6)
Weaningwt	Variate	Not applicable	Liveweight of goat at weaning
			Random effect terms

Agevarlt5	Variate	Not applicable	Age of goat (years) when age ≤ 5, and 5 when age of goat > 5
Agevarlinabove5	Variate	Not Applicable	0 when age ≤ 5, and (age of goat – 5) when age of goat > 5
Seasonvar	Variate	Not applicable	0 for summer shearings and 1 for winter shearings

Table 3. Tests for including and excluding a) fixed effects, b) random individual goat effects, c) random sire effects and d) random dam effects

P-values in bold are significant at the 5% level

Adjustment to model	Wald F-value	Degrees of freedom	*P*-value
(a) Fixed Effects			
Terms included			
Shearyears by Shearregime interaction	7.41	12, 490.3	**1.4×10^{-12}**
Weaningwt effect differs with Breed	5.27	2, 56.1	**0.0080**
LogAdjLwt effect differs with Age1pt5	26.69	1, 183.7	**6.2×10^{-7}**
DOB effect within Age1pt5	2.20	16, 143.4	**0.0075**
Birthwt effect within Age1pt5	9.02	1, 125.0	**0.0032**
Extra Age effect	51.90	5, 93.6	**1.6×10^{-25}**
Terms excluded			
Square of Weaningwt	0.06	1, 86.1	0.82
Square of LogAdjLwt	0.28	1, 440.4	0.60
Square of Birthwt within Age1pt5	0.31	1, 157.0	0.58
DOB outside Age1pt5	1.45	16, 60.0	0.15
Birthwt outside Age1pt5	0.08	1, 76.5	0.78
Breed by Shearregime interaction	0.96	14, 487.6	0.49
Weaningwt effect differs with Shearregime	1.54	7, 510.1	0.15
LogAdjLwt differs with Shearregime	1.24	7, 525.7	0.28
Breed by Age1pt5 interaction	Model did not converge		
Weaningwt differs with Age1pt5	0.30	1, 150.4	0.58
Product of Weaningwt and LogAdjLwt	2.11	1, 209.2	0.15
Single versus Twins	0.48	1, 87.3	0.49
Dam age	2.34	1, 78.6	0.13

Adjustment to model	**Change in deviance χ^2 value**	**Degrees of freedom**	***P-value***
(b) Random Individual goat Effects			
Terms included			
Product of Agevarlt5 and Seasonvar	28.50	5	**2.9×10^{-5}**
Agevarlinabove5	56.96	5	**5.2×10^{-11}**
Terms excluded			
Square of Agevarlt5	Model did not converge		
Product of Agevarlinabove5 and Seasonvar	3.11	6	0.79
Square of Agevarlinabove5	3.11	6	0.79
(c) Random Sire Effects			
Terms included			
Seasonvar effect	16.63	3	**0.00084**
Agevarlt5	25.79	3	**1.0×10^{-5}**
Terms excluded			
Agevarlinabove5	2.00	4	0.74
Product of Agevarlt5 and Seasonvar	Model did not converge		
Square of Agevarlt5	Model did not converge		
(d) Random Dam Effects			
Terms included			
Any dam effect (α)	3.74	1	0.053
Terms excluded			
Agevarlt5 effect	0.23	2	0.89
Seasonvar effect	2.38	2	0.30
Agevarlinabove5	0.45	2	0.80
Age variate effect	0.11	2	0.95

Table 4. Estimates of random parameters in model of the logarithm$_{10}$(mean fibre diameter)

Parameters	Estimate	s.e. (estimate)
Residual variation		
Variance	0.00026	0.000018
Between goat variation [A]		
Variance of intercept (α)	1.6	0.89
Variance of Agevarlt5 coefficient (β_1)	0.02	0.032
Variance of Seasonvar coefficient (β_2)	2.1	0.85
Variance of (Agevarlt5 × Seasonvar) coefficient (β_3)	0.10	0.054
Variance of Agevarlinabove5 coefficient (β_4)	2.4	0.67
Covariance of α and β_1	0.07	0.128
Covariance of α and β_2	-1.4	0.72
Covariance of α and β_3	0.22	0.174
Covariance of α and β_4	0.7	0.53
Covariance of β_1 and β_2	-0.18	0.113
Covariance of β_1 and β_3	0.05	0.029
Covariance of β_1 and β_4	-0.09	0.100
Covariance of β_2 and β_3	-0.4	0.21
Covariance of β_2 and β_4	-1.3	0.53
Covariance of β_3 and β_4	0.19	0.127
Between sire variation [A]		
Variance of intercept (α)	1.3	1.08
Variance of Agevarlt5 coefficient (β_1)	0.08	0.047
Variance of Seasonvar coefficient (β_2)	0.16	0.11
Covariance of α and β_1	-0.10	0.160
Covariance of α and β_2	0.0	0.24
Covariance of β_1 and β_2	-0.11	0.065
Between dam variation		
Variance	0.00058	0.000166

[A] Values presented are multiples of residual variance, i.e. 0.00026.

Table 5. Proportion of total random variance of the logarithm of κ that is associated with systematic animal (including sire and dam) effects $\left(\frac{\sigma^2_{Sire}+\sigma^2_{Dam}+\sigma^2_{Animal}}{\sigma^2_{Sire}+\sigma^2_{Dam}+\sigma^2_{Animal}+\sigma^2_{error}}\right)$**, at each shearing age**

Age of goat (years)	Proportion of variance (R)	s.e. (R)
1	0.79	0.044
2	0.79	0.042
2.5	0.85	0.029
3	0.81	0.036
3.5	0.86	0.027
4	0.84	0.029
4.5	0.87	0.026
5	0.87	0.023
5.5	0.89	0.022
6	0.90	0.018

Table 6. Correlation of the random effects of the logarithm of κ systematically associated with animal ($\sigma^2_{Sire} + \sigma^2_{Dam} + \sigma^2_{Animal}$) between different shearing ages

Age (years)	1	2	2.5	3	3.5	4	4.5	5	5.5
	–	–	–	–	–	–	–	–	–
2	0.94	–	–	–	–	–	–	–	–
2.5	0.64	0.81	–	–	–	–	–	–	–
3	0.78	0.94	0.91	–	–	–	–	–	–
3.5	0.52	0.71	0.97	0.87	–	–	–	–	–
4	0.57	0.78	0.90	0.94	0.92	–	–	–	–
4.5	0.40	0.60	0.88	0.78	0.97	0.89	–	–	–
5	0.40	0.61	0.83	0.83	0.89	0.96	0.90	–	–
5.5	0.33	0.51	0.82	0.69	0.92	0.80	0.96	0.83	–
6	0.34	0.49	0.74	0.65	0.77	0.75	0.76	0.77	0.85