World Academy of Science, Engineering and Technology
International Journal of Agricultural and Biosystems Engineering
Vol:6, No:7, 2012

Influence of Sire Breed, Protein Supplementation and Gender on Wool Spinning Fineness in First-Cross Merino Lambs

A. E. O. Malau-Aduli, B. W. B. Holman, P. A. Lane

Open Science Index, Agricultural and Biosystems Engineering Vol:6, No:7, 2012 publications.waset.org/13858.pdf

Abstract**—**Our objectives were to evaluate the effects of sire breed, type of protein supplement, level of supplementation and sex on wool spinning fineness (SF), its correlations with other wool characteristics and prediction accuracy in F_1 Merino crossbred lambs. Texel, Coopworth, White Suffolk, East Friesian and Dorset rams were mated with 500 purebred Merino dams at a ratio of 1:100 in separate paddocks within a single management system. The F_1 progeny were raised on ryegrass pasture until weaning, before forty lambs were randomly allocated to treatments in a 5 x 2 x 2 x 2 factorial experimental design representing 5 sire breeds, 2 supplementary feeds (canola or lupins), 2 levels of supplementation (1% or 2% of liveweight) and sex (wethers or ewes). Lambs were supplemented for six weeks after an initial three weeks of adjustment, wool sampled at the commencement and conclusion of the feeding trial and analyzed for SF, mean fibre diameter (FD), coefficient of variation (CV), standard deviation, comfort factor (CF), fibre curvature (CURV), and clean fleece yield. Data were analyzed using mixed linear model procedures with sire fitted as a random effect, and sire breed, sex, supplementary feed type, level of supplementation and their second-order interactions as fixed effects. Sire breed ($P<0.001$), sex ($P<0.004$), sire breed x level of supplementation ($P<0.004$), and sire breed x sex ($P<0.019$) interactions significantly influenced SF. SF ranged from 22.7 ± 0.2µm in White Suffolk-sired lambs to 25.1 ± 0.2µm in East Friesian crossbred lambs. Ewes had higher SF than wethers. There were significant ($P<0.001$) correlations between SF and FD (0.93), CV (0.40), CF (-0.94) and CURV (-0.12). Its strong relationship with other wool quality traits enabled accurate predictions explaining up to about 93% of the observed variation. The interactions between sire breed genetics and nutrition will have an impact on the choices that dual-purpose sheep producers make when selecting sire breeds and protein supplementary feed levels to achieve optimal wool spinning fineness at the farmgate level. This will facilitate selective breeding programs being able to better account for SF and its interactions with other wool characteristics.

Keywords**—**Merino crossbred sheep, protein supplementation, sire breed, wool quality, wool spinning fineness

I. INTRODUCTION

THE Australian wool industry has re-situated itself within the dual-purpose livestock system where both meat and wool traits share a production focus using a single flock [1], [2]. This shift is driven by the high demand for sheep meat, especially prime lamb [3], and is expected to continue into the foreseeable future given the comparatively low wool prices [4], stiff competition with wool from artificial fibres [5], [6], recent economic downturn and increased production costs [7]. Dual-purpose systems allow market security and profitability through mating terminal sires with purebred Merino dams [8], [9], thus enabling meat sheep breeders and farmers to exploit maternal and individual heterosis in blending desirable meat and wool traits in the first-cross (F_1) progeny [10], [11], [12]. Furthermore, the provision of protein-rich supplements drives profitability. Canola and lupins are supplementary feeds of choice due to their relatively low costs and easy availability [13], [14], [15]. Both crossbreeding and protein supplementation have been found to impact wool quality.

Wool quality is a function of the fibre characteristics which influence processing performance and ultimate end usefulness [16], [17], [18]. Therefore, price incentives exist for wool of commercially determined characteristics. Spinning fineness (SF) is one of the wool quality characteristics widely assessed, and it is a refinement of two key wool quality attributes - mean fibre diameter (FD) and coefficient of variation (CV) [19], into a single value [20], [21]. Consequently, SF permits accurate comparison and estimation of wool processing speed, cost, and yarn evenness [22], [23], attributes that meet the manufacturer's demand for top-quality wool. Low SF wool is typically more desirable and financially rewarded [24]. The main objective of this study was to quantify at the farmgate level, the influences of sire genetics, sex, protein supplement type, level of supplementation and their interactions on SF, its correlations with other wool characteristics and prediction accuracy in F1 Merino crossbred prime lambs.

II. MATERIALS AND METHODS

A. Animal Ethics, Management and Experimental Design

This study was conducted at the University of Tasmania Farm, Cambridge, Tasmania, Australia. All procedures had University of Tasmania Animal Ethics approval and were conducted in accordance with the 1993 Tasmanian Animal Welfare Act and the 2004 Australian Code of Practice for the Care and Use of Animals for Scientific Purposes. The data were generated from a sheep crossbreeding experimental flock

A. E. O. Malau-Aduli is with Animal Science and Genetics, School of Agricultural Science, Tasmanian Institute of Agriculture, University of Tasmania, Private Bag 54 Hobart, Tasmania 7001, Australia (phone: 613-6226-2717; fax: 613-6226-2642; e-mail: aduli.malauaduli@utas.edu.au).

B. W. B. Holman is with Animal Science and Genetics, School of Agricultural Science, Tasmanian Institute of Agriculture, University of Tasmania, Private Bag 54 Hobart, Tasmania 7001, Australia (phone: 613-6226-2717; fax: 613-6226-2642; e-mail: benjamin.holman@utas.edu.au).

P. A. Lane is with Animal Science and Genetics, School of Agricultural Science, Tasmanian Institute of Agriculture, University of Tasmania, Private Bag 54 Hobart, Tasmania 7001, Australia (phone: 613-6226-2717; fax: 613-6226-2642; e-mail: peter.lane@utas.edu.au).

Open Science Index, Agricultural and Biosystems Engineering Vol:6, No:7, 2012 publications.waset.org/13858.pdf

as detailed in Malau-Aduli and Akuoch 2012; Malau-Aduli et. al. 2012; Malau-Aduli and Holman, 2010; Malau-Aduli and Deng Akuoch 2010; Malau-Aduli et al., 2009a; Malau-Aduli et al., 2009b; Malau-Aduli et al., 2009c, d; Malau-Aduli et al., 2009e; Holman et al. 2012.

B. Wool Analysis

Midside wool samples of approximately 10cm^2 (~0.02kg) were shorn from all lambs by an experienced shearer using Oster-Sunbeam electric shears (Baxter and Cottle, 1997), at the beginning and end of the trial. Samples were then commercially analyzed by the Australian Wool Testing Authority (AWTA, Melbourne) for wool SF, FD, CV, standard deviation (SD), fibre curvature (CURV), comfort factor (CF) and clean fleece yield (YIELD).

C. Statistical analyses

Statistical Analysis System (SAS) software [35] was used to initially compute the summary statistics of wool traits by sire breed, sex, protein supplement type and level of supplementation to identify any data entry errors or outliers, through examination of mean, standard deviation, minimum, maximum and range of values.

Mixed Model (PROC MIXED) analyses were then run with sire fitted as a random effect; while sire breed, gender, supplementary feed, level of supplementation, and their second-order interactions were fitted as fixed effects; and SF, FD, CV, SD, CF, CURV, and YIELD as dependent variables. Significant differences between means were established at the P<0.05 level using both Tukey and Duncan's multiple range tests.

Pearson correlation coefficients between SF and other wool traits were computed using PROC CORR [35] and significance established by Bonferroni probability pairwise comparison test. Predictive equations for estimating SF from other wool traits were developed using simple linear, logarithmic, polynomial and exponential regressions in PROC REG [35] and the accuracy of prediction inferred from the coefficient of determination (R^2).

III. RESULTS

The chemical composition (%) of the canola meal, cracked lupins, barley and molasses-treated straw fed to the sheep is portrayed in Table 1. It was apparent that canola and barley had higher digestibility and metabolisable energy values than lupins and straw. Canola also had higher fat and ash contents than lupins and the basal diet of barley and molasses-treated straw. However, dry matter content was similar in the experimental and basal diets. The summary statistics in Table 2 depict the unadjusted values of wool quality attributes in sheep where SF ranged from 17.8 to 28.90µm with an average of 23.9±0.27 µm.

A. Influence of Fixed Effects on Wool Spinning Fineness

Sex was a highly significant (*P<0.004*) source of SF variation in first-cross Merino lambs (Table 3) because ewes produced wool of higher SF value (24.5 ± 0.3µm) than wethers (22.9 ± 0.4µm). It was also evident that the effect of sire breed on SF was very highly significant (P<0.001) in which East Friesian, Dorset and Texel-sired lambs produced wool with higher SF (25.1 ± 0.21µm, 24.3 ± 0.18 µm and 24.0 ± 0.20 µm, respectively) than Coopworth- (23.1 ± 0.16 µm) and White Suffolk-sired lambs with the lowest SF (22.7 ± 0.16 µm) (Table 3). Conversely, the impacts of supplementary protein type and level of supplementation on SF in F_1 Merino crossbred lambs were statistically non-significant (P>0.144 and P>0.064, respectively).

B. Effect of Second-Order Interactions on Wool Spinning Fineness

SF was significantly (P<0.019) influenced by the interaction between sire breed and sex as depicted in Fig. 1. It was also evident that ewe lambs produced wool with significantly (P<0.05) higher SF than wethers when the sire breeds were Coopworth (23.7 ± 0.8 µm and 22.1 ± 0.4 µm respectively), Dorset (25.1 ± 0.5 µm and 22.7 ± 0.6 µm), or White Suffolk (24.0 ± 0.4 µm and 19.8 ± 0.6 µm). No significant variation (P>0.05) was apparent between sexes of East Friesian- or Texel-sired lambs (Fig. 1).

The interaction between sire breed and level of supplementation significantly (*P<0.004*) influenced SF (Fig. 1) because East Friesian-sired crossbred lambs supplemented at 2%LWT had higher SF (26.9 ± 0.5µm) than their counterparts supplemented at 1%LWT (23.2 ± 0.3µm). A similar trend was observed in White Suffolk-sired crossbred lambs as 2%LWT supplementation resulted in higher SF (24.0 ± 0.3µm) than at 1%LWT (21.9 ± 0.5µm). On the other hand, Coopworth, Dorset and Texel sired lambs were not influenced by the level of supplementation (P>0.05).

Supplementary feed type and level of supplementation interaction had a highly significant (P<0.001) effect on SF (Fig. 1) because lambs supplemented with canola at 2%LWT had higher SF values (24.8 ± 0.5 µm) than at 1% LWT (22.4 ± 0.5 µm); a trend that was not observed in lupin-supplemented lambs (P>0.05).

C. Relationships between Spinning Fineness and other Wool Characteristics

SF had highly significant (P<0.001) and positive correlations with mean fibre diameter (0.93), coefficient of variation (0.40) and standard deviation (0.81), but was negatively correlated with comfort factor (-0.94) and fibre curvature (-0.12). Wool yield on the other hand, was not significantly (P>0.05) correlated with SF (Table 4).

Comparisons between simple linear, logarithmic, polynomial and exponential regression analyses in predicting SF (Table 5) indicated that polynomial regression analysis provided the most accurate prediction of SF variation from mean fibre diameter (R^2 = 0.92). Both linear and polynomial regressions gave the best prediction of SF from standard deviation (R^2 = 0.65). Logarithmic and polynomial regressions gave the most accurate prediction of SF from comfort factor (R^2 = 0.93), while SF prediction from coefficient of variation explained only about 15% of the observed variation (R^2 = 0.15). The lowest R^2 and by implication, the worst predictor of SF, was fibre curvature (R^2 = 0.02).

Open Science Index, Agricultural and Biosystems Engineering Vol:6, No:7, 2012 publications.waset.org/13858.pdf

IV. DISCUSSION

Spinning fineness (SF) is an extensively monitored wool characteristic that enables prediction and comparative analysis of diverse wool samples during processing. The potential economic significance of SF has prompted suggestions that it is one of the key wool characteristics that should be taken into cognizance when designing breeding programs and objectively quantifying wool quality [36], [24], [23]. Our findings in this study demonstrated that SF in crossbred Merino lambs was influenced by sire breed, sex and their interactions with dietary protein source and supplementation level because 1%LWT canola-supplemented, White Suffolk-sired, wether progeny had the lowest and most desirable SF. This knowledge would be useful for dual-purpose sheep farmers in making informed management choices and cost effective supplementation strategies at the farmgate level for attaining optimal SF. Previous investigations on the effect of sex on wool growth suggested that observed differences between the genders were attributable to hormonal variations [37], [38], [39]. Published literature indicates that testosterone, the testis-produced male sex hormone, stimulates wool synthesis and coarser fibre production [40], [39], while progesterone, an ovary-secreted female sex hormone, is associated with finer wool fibres [37], [38]. However, these findings differ from those found in our study. This divergence may well be expected given the fact that in this study, only wethers (castrated males) instead of intact males, were utilized. The subsequent interference of testicle removal on the male endocrine systems possibly led to the decline in testosterone production resulting in finer wool growth in the wethers compared with their intact peers [41], [42]. Also, in male sheep, the partitioning of absorbed nutrients tends to tilt more towards body growth as opposed to wool growth than in females, potentially accentuated in this study through the inclusion of paternal carcass trait genes [34], [37]. However, wether and ewe SF variations could potentially be also due to differences in body size and feed intake rather than feed to wool conversion [43], [34]. The significant influence of sire breed on SF followed the expected pattern because SF has been documented to be strongly correlated with mean fibre diameter which is known to be highly heritable (0.65 ± 0.01) and dependent on paternal genetics [44], [24], [45], [1], [10], [38], [46], [47]. Furthermore, it can be construed that the variation in mean fibre diameter was mainly attributable to the sire because it was the key determinant of the F_1 progeny's fibre diameter and spinning fineness since maternal effects were minimized by the use of Merino dams only across all sire breeds [25]. This is supported by literature where sire breed ranking by mean fibre diameter and SF was similar to our study: East Friesian (~40μm), Texel (28-33μm), Dorset (25-30μm), Coopworth (~35μm) and White Suffolk (25-30μm) [48], [49], [50]. Heterosis would have also had an impact on our observed SF values as evidence from published literature suggests that it is reliant on genotype, varying with sire breed by approximately 2% because of reductions in follicle density and subsequent increase in fibre coarseness [51], [37], [52].

Also, total follicle density and secondary to primary follicle ratios differ among sire breeds, thereby influencing SF and potentially causing identified variations [37].

The observed significant sire breed and sex interaction effect on SF implies that ewe and wether lambs of the same sire breed produced wool of varied spinning fineness which could possibly stem from genotypic differences resulting from evolutionary dimorphism. Male and female sheep are phenotypically unlike mainly due to sex chromosomal divergence (X and Y). This variation naturally arose from sexual selection with male castrates developing female-like characteristics, including large body size, subsequently achieving greater mating access to females than smaller and less appealing males, thereby producing more progeny [53], [54]. Also, the disparity in physiological maturity between sire breeds affects wool and SF development [55].

The significant influence of the interaction between sire breed and level of supplementation on SF could have been triggered by gene-regulatory mechanisms that shift nutrient supply and partitioning, including intake, availability and uptake for wool growth [56], [57]. That genetic variations impact nutrient partitioning is a well documented concept [58], [59], [46]. Purebred Merinos partition 20-25% of total absorbed protein towards wool synthesis, with 10-15% actively transformed into wool, indicating greater dietary protein, or supplementation level, which equates to higher wool growth and SF values [13], [31], [32], [33], [38], [60]. The impact of paternal heterosis in this study seem to imply that the nutrient partitioning favored carcass growth as the norm is in dual-purpose production systems [61] who also found that joining meat rams over Merino ewes resulted in a decrease in wool follicle density in the progeny thereby causing coarser wool fibres with higher SF and wool comfort factor [28], [25].

Thus, the use of various meatsheep sire breeds has resulted in varied compromise of high wool quality from Merino maternal genes through more emphasis on carcass growth [61], [62]. Consequently, our results demonstrate that sire breeds have differing impacts on wool production potential and response to increased feed. The observed increase in SF with increasing levels of canola supplementation but not lupins in our study was potentially caused by differences in nutritional composition and digestibility, as higher feed consumption of protein-rich feeds results in higher wool growth and SF [63], [13], [27], [64], [38], [65], [60]. A comparison of protein content between supplementary feeds has shown that canola contains more protein than lupins [2 g/100 g DM and 0.4-1 g/100 g DM respectively] [13]. Moreover, wool growth is limited by sulphur amino acids availability, predominantly methionine and cysteine, and as a proportion of DM canola contains more than lupins, 1.65% to 0.8% respectively [63], [61], [67], [13], [64], [65]. However, sulphur amino acids only significantly contribute to wool synthesis upon bypassing rumen degradation and entering the abomasum, therefore, sulphur-containing amino acids in dietary protein sources should be rumen-protected [63], [66]. Canola protein is less prone to rumen degradation than lupins (about 48% and 85% loss respectively), thus increasing canola supplementation results in substantial increases in rumen-protected, sulphur-containing amino acids compared with increased lupin supplementation, hence justifying the higher wool growth and SF values [65].

As SF is mathematically derived from FD and CV, their strongly positive correlations are logical and expected [24], [22], [47], [19]. The strongly negative correlations between SF CF and CURV in this study agree with similar reports in the literature [23], [36], [68], [69] [70]. These relationships were further explored using regression analyses to develop SF predictive equations.

V. CONCLUSIONS

The influence of sire genetics and protein supplementation on wool spinning fineness at the farmgate level was investigated in first-cross Merino lambs sired by five genetically divergent rams. Evidence demonstrated that sire breed and sex as well as interactions with protein supplementation had significant impacts on wool spinning fineness. Its strong relationship with other wool quality traits enabled accurate predictions explaining up to about 93% of the observed variation. These interactions between sire breed genetics and nutrition will have an impact on the choices that dual-purpose sheep producers make when selecting sire breeds and protein supplementary feed levels to achieve optimal wool spinning fineness at the farmgate. Future investigations which include purebred Merino lambs and alternative protein supplementation types exposed to similar treatments would complement our findings by permitting comparisons against specialist wool producers.

ACKNOWLEDGEMENTS

This research was funded by grants and scholarships from the Australian Wool Education Trust (AWET), The Commonwealth Scientific and Industrial Research Organisation (CSIRO) Food Futures National Flagship and The University of Tasmania (UTAS). We appreciate the valuable inputs of Will Bignell, Jane Sykes, Courtney Ranson, Ruth Walker, Samuel Adediran, Stephen Ridge, Angela Geard, Marek Matuszek and Jurkuch Deng Akuoch who contributed to the field work during the sheep crossbreeding and feeding trials. Our gratitude also goes to the following Tasmanian Sheep Stud Breeders who donated their rams for the experiment: Chris and Rodney Gunn, Brammel Hazelwood, Rob Henry, Tony Burns and Michael French.

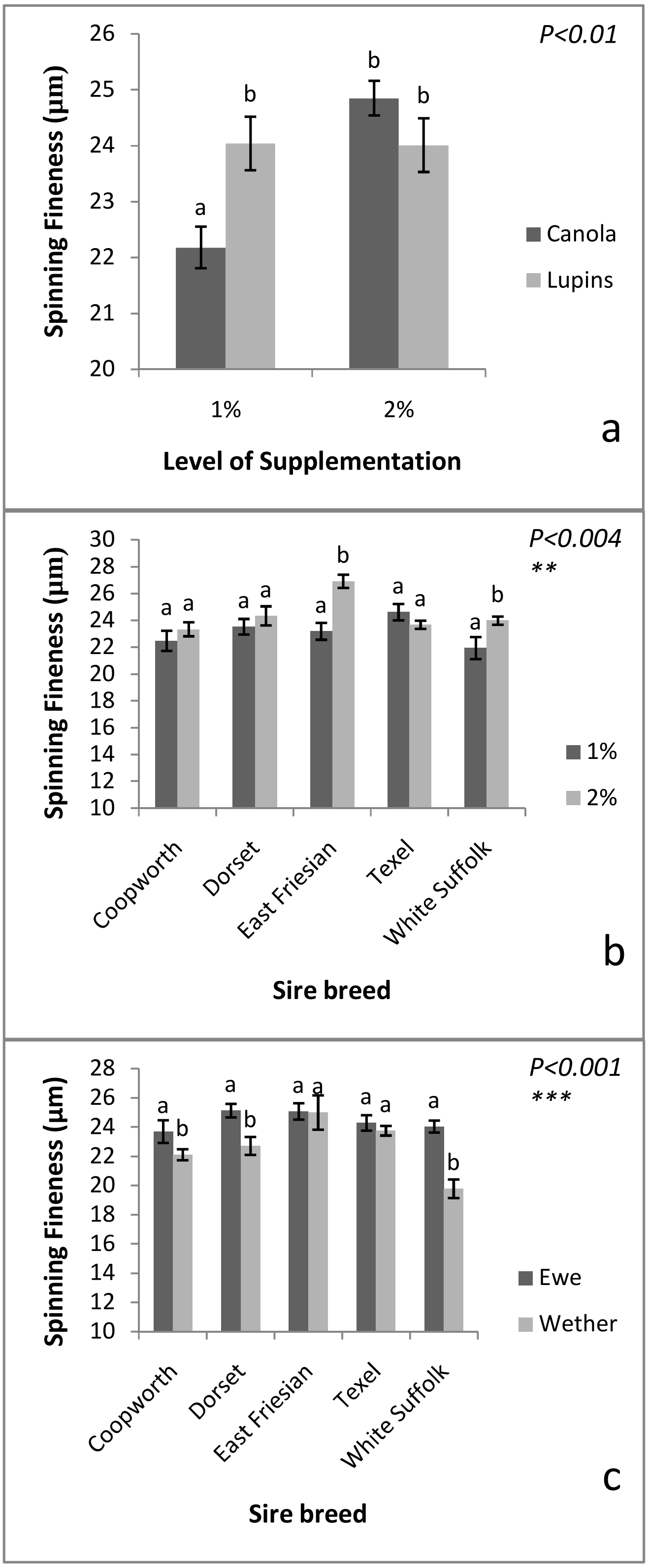

Fig. 1 The interactions between a) level of supplementation and supplementary feed, b) sire breed and level of supplementation, c) sire breed and sex, and the level of significance (*P values*) on SF in F_1 crossbred Merino lambs. Means bearing different superscripts significantly differ (*$P<0.05$*)

TABLE I
NUTRIENT COMPOSITION OF SUPPLEMENTARY AND BASAL DIETS FOR F_1 MERINO LAMBS

Nutrient[1]	Canola Meal	Cracked Lupins	Barley	Molasses-straw
DM (%)	96.3	93.3	92.0	92.5
Crude Fibre (%)	13.8	15.7	4.6	41.3
NDF (%)	18.9	25.0	14.4	66.4
ADF (%)	15.9	20.9	5.5	43.4
ME (MJ/KG)	14.9	12.2	13.2	7.3
DE (MJ/KG)	277.3	183.7	213.3	62.3
Feed Digestibility	60.0	40.0	60.0	20.0
N (%)	5.3	4.8	1.7	1.0
CP (%)	33.3	30.1	10.4	6.2
Fat (%)	15.8	6.0	2.3	1.0
Ash (%)	5.9	2.7	2.5	9.6

[1] Dry matter (DM), neutral detergent fibre (NDF), acid detergent fibre (ADF), metabolisable energy (ME), digestible energy (DE), Nitrogen (N), and crude protein (CP)

TABLE II
SUMMARY STATISTICS OF WOOL QUALITY ATTRIBUTES IN F_1 MERINO LAMBS

Attribute[1]	Mean ± Standard Deviation	Minimum	Maximum	Range
SF (µm)	23.9 ± 0.3	17.8	28.9	11.1
FD (µm)	24.3 ± 0.3	17.2	29.5	12.3
SD	5.3 ± 0.1	3.3	7.9	4.6
CV (%)	21.9 ± 0.4	14.8	29.2	14.4
CF (%)	85.9 ± 1.1	56.7	99.5	42.8
CURV (°/mm)	71.3 ± 1.1	48.0	93.0	45.0

[1] Wool spinning fineness (SF), fibre diameter (FD), coefficient of variation (CV), standard deviation (SD), comfort factor (CF), and Curvature (CURV)

TABLE III
LEVELS OF SIGNIFICANCE (*P* -VALUES), LEAST SQUARE MEANS AND STANDARD ERROR (LSM ± SE) OF SPINNING FINENESS (µM) BY SIRE BREED, SUPPLEMENTARY FEED, LEVEL OF SUPPLEMENTATION AND SEX IN F_1 MERINO LAMBS

Fixed effects		Spinning Fineness[1]
Sire breed	Coopworth	23.1 ± 0.2^{bc}
(P>0.001***)	Dorset	24.0 ± 0.2^{abc}
	East Friesian	25.1 ± 0.2^{a}
	Texel	24.3 ± 0.2^{ab}
	White Suffolk	22.7 ± 0.2^{c}
Supplementary feed	Canola	23.6 ± 0.4
(P>0.144^{NS})	Lupins	24.3 ± 0.4
Level of supplementation	1%	23.1 ± 0.3
(P>0.064^{NS})	2%	24.5 ± 0.3
Sex	Ewe	24.5 ± 0.3^{a}
(P<0.004**)	Wether	22.9 ± 0.4^{b}

[1] Column, means within a fixed effect bearing different superscripts significantly differ ($P<0.05$).
Levels of significance: ^{NS} not significant ($P>0.05$), ** highly significant ($P<0.01$), *** very highly significant ($P<0.001$)

TABLE IV
PEARSON CORRELATION COEFFICIENTS BETWEEN WOOL QUALITY TRAITS IN CROSSBRED F_1 MERINO LAMBS[1]

Wool trait	SF	FD	CV	SD	CF	CURV	YIELD
SF		0.93***	0.40***	0.81***	-0.94***	-0.12**	0.09
FD	0.93***		0.13**	0.60***	-0.85***	-0.10*	0.11*
CV	0.40***	0.13**		0.86***	-0.45***	-0.14**	-0.08
SD	0.81***	0.60***	0.86***		-0.81***	-0.16***	0.04
CF	-0.94***	-0.85***	-0.45***	-0.81***		0.11**	-0.09
CURV	-0.12**	-0.10*	-0.14**	-0.16***	0.11**		-0.10*
YIELD	0.09	0.11**	-0.08	0.04	-0.09	-0.10*	

[1] Level of significance: * significant (*P*<0.05), ** highly significant (*P*<0.01), *** very highly significant (*P*<0.001). Wool spinning fineness (SF), fibre diameter (FD), coefficient of variation (CV), standard deviation (SD), comfort factor (CF), and fibre curvature (CURV)

TABLE V
PREDICTION OF (Y) SPINNING FINENESS (μM) FROM MEAN FIBRE DIAMETER (μM), COEFFICIENT OF VARIATION (%), STANDARD DEVIATION (μM), COMFORT FACTOR (%), FIBRE CURVATURE (°/MM) USING SIMPLE LINEAR, LOGARITHMIC, POLYNOMIAL AND EXPONENTIAL REGRESSION ANALYSIS OF F1 MERINO CROSSBRED LAMBS

Independent variable (x)	Linear	Logarithmic	Polynomial	Exponential
FD	y= 1.014x-0.775	y= 23.12ln(x)-49.88	$y= 0.007x^2+0.682x+3.024$	$y= 7.974e^{0.045x}$
	$R^2=0.922$	$R^2=0.916$	$R^2=0.923$	$R^2=0.922$
SD	y= 2.011x+12.44	y= 9.925ln(x)+6.654	$y= 0.016x^2+1.846x+12.85$	$y= 14.37e^{0.088x}$
	$R^2=0.648$	$R^2=0.639$	$R^2=0.648$	$R^2=0.641$
CV	y= 0.274x+16.46	y= 5.95ln(x)+4.157	$y= -0.005x^2+0.529x+13.70$	$y= 17.18e^{0.012x}$
	$R^2=0.146$	$R^2=0.147$	$R^2=0.147$	$R^2=0.144$
CF	y= -0.277x+47.81	y= -23.3(ln)+127.9	y= -0.005x2+0.643x+8.262	$y= 67.44e^{-0.01x}$
	$R^2=0.886$	$R^2=0.925$	$R^2=0.925$	$R^2=0.852$
CURV	y= -0.018x+23.71	y= -1.41(ln)x+28.39	$y= 6E-05x^2+0.027x+24.05$	$y= 23.65e^{-8E-0x}$
	$R^2=0.019$	$R^2=0.018$	$R^2=0.019$	$R^2=0.019$

Fibre diameter (FD), coefficient of variation (CV), standard deviation (SD), comfort factor (CF), fibre curvature (CURV) and R^2=*coefficient of determination*

REFERENCES

[1] N. M. Fogarty, E. Safari, A. R. Gilmour, V. M. Ingham, K. D. Atkins, S. I. Mortimer, A. A. Swan, F. D. Brien, and J. H. J. van der Werf, “Wool and meat genetics: The joint possibilities”, *International Journal of Sheep Wool Science*, vol. 54, pp. 22-27, 2006.

[2] E. Safari, N. M. Fogarty, and A. R. Gilmour, “A review of genetic parameter estimates for wool, growth, meat and reproduction traits in sheep”, *Livestock Production Science*, vol. 92, pp. 271-289, 2005.

[3] J. C. Greeff, E. Safari, N. M. Fogarty, D. L. Hopkins, F. D. Brien, K. D. Atkins, S. I. Mortimer, and J. H. J. van der Werf. 2008, “Genetic parameters for carcass and meat quality traits and their relationships to liveweight and wool production in hogget Merino rams”, *Journal of Animal Breeding and Genetics*, vol. 125, pp. 205-215, 2008.

[4] K. J. Harle, S. M. Howden, L. P. Hunt, and M. Dunlop, “The potential impact of climate change on the Australian wool industry by 2030”, *Agricultural Systems*, vol. 93, pp 61-89, 2007.

[5] I. W. Purvis, and I. R. Franklin, “Major genes and QTL influencing wool production and quality: A review”, *Genetic Selection and Evolution*, vol. 37, pp. S97-S107, 2005.

[6] M. Valera, F. Arrebola, M. Juárez, and A. Molina, “Genetic improvement of wool production in Spanish Merino sheep: genetic parameters and simulation of selection strategies”, *Animal Production Science*, vol. 49, pp. 43-47, 2009.

[7] J. B. Rowe, “The Australian sheep industry – undergoing transformation. *Animal Production Science*, vol. 50, pp. 991-997, 2010.

[8] H. D. Daetwyler, J. M. Hickey, J. M. Henshall, S. Dominik, B. Gredler, J. H. J. van der Werf, and B. J. Hayes, “Accuracy of estimated genomic breeding values for wool and meat traits in a multi-breed sheep population”, *Animal Production Science*, vol. 50, pp. 1004-1010, 2010.

[9] E. Kopke, J. Young, and R. Kingwell, “The relative profitability and environmental impacts of different sheep systems in a Mediterranean environment”, *Agricultural Systems*, vol. 96, pp. 85-94, 2008.

[10] S. I. Mortimer, D. L. Robinson, K. D. Atkins, F. D. Brien, A. A. Swan, P. J. Taylor, and N. M. Fogarty, “Genetic parameters for visually assessed traits and their relationships to wool production and liveweight in Australian Merino sheep”, *Animal Production Science*, vol. 49, pp. 32-42, 2009.

[11] G. Refshauge, S. Hatcher, G. N. Hinch, D. L. Hopkins, and S. Nielsen, “Fat depth, muscle depth, fat score and wool growth in Merino dams selected for high or low clean fleece weight and bodyweight”, *Animal Production Science*, vol. 50, pp. 479-484, 2010.

[12] P. K. Thornton, “Livestock production: recent trends, future prospects”, *Philosophical Transactions of the Royal Society B-Biological Sciences*, vol. 365, pp. 2853-2867, 2010.

[13] S. M. Liu, and D. G. Masters, “Amino acids utilization for wool production”, In: *Amino acids in animal nutrition*, J. P. F. D'Mello (Editor), CAB International, Wallingford, UK, pp. 309-328, 2003.

[14] D. Masters, and G. Mata, “Responses to feeding canola meal or lupin seed to pregnant, lactating, and dry ewes”, *Australian Journal of Agricultural Research*, vol. 47, pp. 1291-1303, 1996.

[15] C. L. White, L. M. Tabe, H. Dove, J. Hamblin, P. Young, N. Phillips, R. Taylor, S. Gulati, J. Ashes and T. J. V. Higgins, “Increased efficiency of wool growth and live weight gain in Merino sheep fed transgenic lupin seed containing sunflower albumin. *Journal of the Science of Food and Agriculture*, vol. 81, pp. 147-154, 2001.

[16] C. Angel, S. Beare, and A. C. Zwart, "Product characteristics and arbitrage in the Australian and New Zealand wool markets", *Australian Journal of Agricultural Economics*, vol. 34, pp. 67-79, 1990.

[17] F. Bidinost, D. L. Roldan, A. M. Dodero, E. M. Cano, H. R. Taddeo, J. P. Mueller, and M. A. Poli, “Wool quantitative trait loci in Merino sheep”, *Small Ruminant Research*, vol. 74, pp. 113-118, 2008.

[18] M. J. Kelly, A. A. Swan, and K. D. Atkins, “Optimal use of on-farm fibre diameter measurement and its impact on reproduction in commercial Merino flocks”, *Australian Journal of Experimental Agriculture*, vol. 47, pp. 525-534, 2007.

[19] A. F. Botha, and L. Hunter, “The measurement of wool fibre properties and their effect on worsted processing performance and product quality. Part 1: The objective measurement of wool fibre properties”, *Textile Progress*, vol. 42, pp. 227-339, 2010.

[20] J. Aylan-Parker, and B. A. McGregor, “Optimising sampling techniques and estimating sampling variance of fleece quality attributes in alpacas”, *Small Ruminant Research*, vol. 44, pp 53-64, 2002.

[21] B. P. Baxter, and D. J. Cottle, “The use of midside fleece fibre diameter distribution measurements in sheep selection”, *Wool Technology and Sheep Breeding*, vol. 46, pp. 154-171, 1998.

[22] C. Deng, L. Wang, and X. Wang, “Diameter variations of irregular fibers under different tensions”, *Fibers and Polymers*, vol. 8, pp. 642-648, 2007.

[23] G. R. S. Naylor, D. G. Phillips, and C. J. Veitch, “The relative importance of mean diameter and coefficient of variation of sale lots in determining the potential skin comfort of wool fabrics”, *Wool Technology and Sheep Breeding*, vol. 43, pp. 69-82, 1995.

[24] K. L. Butler, and M. Dolling, “Merino fleece spinning fineness”, *Wool Technology and Sheep Breeding*, vol. 50, pp. 626-631, 2002.

[25] A. E. O. Malau-Aduli, and J. D. D. Akuoch, "Sire genetics, protein supplementation and gender effects on wool comfort factor in Australian crossbred sheep", *American Journal of Experimental Agriculture*, vol. 2, pp. 31-46, 2012.

[26] A. E. O. Malau-Aduli, E. Nightingale, P. McEvoy, J. U. Eve, A. J. John, A. A. Hobbins, A. A. S. Alamoudi, K. R. Petrie, P. Damen, M. E. French, A. M. Cragie, S. K. Bales, A. Kashani, B. W. B. Holman, J. Vargas-Bravo, S. M. Jones, B.S. Malau-Aduli and P. A. Lane, "Teaching Animal Science and Genetics to Australian university undergraduates to enhance inquiry-based student learning and research with sheep: Growth and conformation traits in crossbred prime lambs", *British Journal of Educational Research* vol. 2, pp. 59-76, 2012.

[27] A. E. O. Malau-Aduli, and B. Holman, “Genetics-nutrition interactions influencing wool spinning fineness in Australian crossbred sheep”, *Journal of Animal Science*, vol. 88 (E-Suppl. 2), pp. 469, 2010.

[28] A. E. O. Malau-Aduli, and D. J. Deng Akuoch, “Wool comfort factor variation in Australian crossbred sheep”, *Journal of Animal Science*, vol. 88 (E-Suppl. 2), pp. 860, 2010.

[29] A. E. O. Malau-Aduli, C. F. Ranson, and C. W. Bignell, “Wool quality and growth traits of Tasmania pasture-fed crossbred lambs and relationships with plasma metabolites”, *Journal of Animal Science*, vol. 87 (E-Suppl. 2), pp. 499, 2009a.

[30] A. E. O. Malau-Aduli, R. E. Walker, and C. W. Bignell, “Prediction of wool fibre diameter from protein and metabolisable energy digestibility coefficients in crossbred sheep”, *Journal of Animal Science*, vol. 87 (E-Suppl. 2), pp. 498, 2009b.

[31] A. E. O. Malau-Aduli, J. M. Sykes, and C. W. Bignell, “Influence of lupins and canola supplements on plasma amino acids, wool fibre diameter and liveweight in generally divergent first cross Merino lambs”, *Proceedings of the World Congress on Oils and Fats and 28th International Society of Fats Research Congress*, September 2009, Sydney Convention &Exhibition Centre, Sydney, New South Wales, Australia, vol. 28, pp. 27-30, 2009c.

[32] A. E. O. Malau-Aduli, R. E. Walker, and C. W. Bignell, “Variation in sire genetics is an irrelevant determinant of digestibility in supplemented crossbred sheep”, In: Ruminant Physiology: Digestion, metabolism and effects of nutrition on reproduction and welfare, Y. Chilliard, F. Glasser, Y. Faulconnier, F. Bocquier, I. Veissier, and M. Doreau (Editors). *Proceedings of the XIth International Symposium on Ruminant Physiology*, 6-9 September 2009, Clermont-Ferrand, France, Wageningen Academic Publishers, Netherlands, pp. 278-279, 2009d.

[33] A. E. O. Malau-Aduli, R. E. Walker, C. F. Ranson, J. M. Sykes, and C. W. Bignell, “Nutrition-genetics interaction in nutrient utilisation of canola and lupins by Australian sheep: Prediction of wool fibre diameter. *Proceedings of the 7th International Workshop on Modelling Nutrient Digestion and Utilisation in Farm Animals*, AgroParisTech, Paris, France, pp. 50, 2009e.

[34] B. W. B. Holman, A. Kashani, and A. E. O. Malau-Aduli, "Growth and body conformation responses of genetically divergent Australian sheep to Spirulina (Arthrospira platensis) supplementation", *American Journal of Experimental Agriculture*, vol. 2, pp.160-173, 2012.

[35] Statistical Analysis System, SAS Institute, version 9.2, Cary, NC, USA, 2009.

[36] G. R. S. Naylor, “Fabric-evoked prickle in worsted spun single jersey fabric, Part 4: Extension from wool to OptimTMfine fiber”, *Textile Research Journal*, vol. 80, pp. 537-547, 2010.

[37] W. S. Pitchford, “Effect of crossbreeding on components of Hogget wool production”, *Australian Journal of Agricultural Research*, vol. 43, pp. 1417- 1427, 1992.

[38] J. M. Sachse, “Sheep production and management”, New Mexico State University, Agricultural and Home Economics, Las Cruces, USA, 2008.

[39] A. L. C. Wallace, “The effect of hormones on wool growth”, In: Physiological and environmental limitations to wool growth, J. L. Black, and P. J. Reis (Editors), *Proceedings of National Workshop on Wool*, Leura, New South Wales, Australia., University of New England Publishers, Armidale, Australia, pp. 115-126, 1979.

[40] S. B. Slen, and R. Connell, “Wool growth in sheep as affected by the administration of certain sex hormones”, *Canadian Journal of Animal Science*, vol. 38, pp. 38-47, 1958.

[41] J. Egan, and D. Russell, “Growth and wool production of wethers and induced cryptorchids in a Poll Merino flock”, *Australian Journal of Experimental Agriculture*, vol. 21, pp. 268-271, 1981.

[42] T. G. Jenkins, J. J. Ford, and J. Klindt, “Postweaning growth, feed efficiency and chemical composition of sheep as affected by prenatal and post-natal testosterone”, *Journal of Animal Science*, vol. 66, pp. 1179-1185, 1988.

[43] G. E. Rogers, and A. C. Schlink, “Wool growth and production”, In: *International Sheep and Wool Handbook*, D. J. Cottle (Editor), Nottingham University Press, Nottingham, UK, pp. 373-394, 2010.

[44] R. Bunge, D. L. Thomas, T. G. Nash, and C. J. Lupton, “Performance of hair breeds and prolific wool breeds of sheep in southern Illinois: wool production and fleece quality”, *Journal of Animal Science*, vol. 74, pp. 25-30, 1996.

[45] N. M. Fogarty, V. M. Ingham, A. R. Gilmour, L. J. Cummins, G. M. Gaunt, J. Stafford, J. E. Hocking Edwards and R. Banks, “Genetic evaluation of crossbred lamb production. 2. Breed and fixed effects for post-weaning growth, carcass, and wool of first-cross lambs”, *Australian Journal of Agricultural Research*, vol. 56, pp. 455-463, 2005.

[46] G. H. Scales, A. R. Bray, D. B. Baird, D. O'Connell, and T. L. Knight, “Effect of sire breed on growth, carcass, and wool characteristics of lambs born to Merino ewes in New Zealand”, *New Zealand Journal of Agricultural Research*, vol. 43, pp. 93-100, 2000.

[47] E. Wood, “Textile properties of wool and other fibres”, *Wool Technology and Sheep Breeding*, vol. 51, pp. 272-290, 2003.

[48] D. J. Cottle, “World sheep and wool production”, In: *International Sheep and Wool Handbook*, D. J. Cottle (Editor), Nottingham University Press, Nottingham, UK, pp. 1-49, 2010.

[49] A. H. Farid, and M. H. Fahmy, “The East Friesian and other European breeds” In: *Prolific Sheep*, M. H. Fahmy (Editor), CAB International, Wallingford, UK, pp. 93-108, 1996.

[50] C. P. Mathis, and B. Faris, “Wool grades: Guide B-409”, New Mexico State University, Agricultural and Home Economics, Las Cruces, 2002.

[51] J. R. Gillespie and F. B. Flanders, “Modern livestock and poultry production”, Delmar Cengage Learning, Clifton Park, NY, 8th ed., 2010.

[52] G. M. Sidwell, R. L. Wilson, and M. E. Hourihan, “Production in some pure breeds of sheep and their crosses. IV. Effect of crossbreeding on wool production”, *Journal of Animal Science*, vol. 32, pp. 1099-1102, 1971.

[53] A. Kodric-Brown, and J. H. Brown, “Truth in Advertising: The kinds of traits favored by sexual selection”, *The American Naturalist*, vol. 124, pp. 309-323, 1984.

[54] B. T. Preston, I. R. Stevenson, J. M. Pemberton, and K. Wilson, “Dominant rams lose out by sperm depletion - A waning success in siring counters a ram's high score in competition for ewes”, *Nature*, vol. 409, pp. 681-682, 2001.

[55] R. B. Land, “Reproduction in young sheep: some genetic and environmental sources of variation”, *Journal of Reproduction and Fertility*, vol. 52, pp. 427- 436, 1978.

[56] P. B. Cronjé, “Nutrient partitioning”. In: *Ruminant Physiology: Digestion, Metabolism, Growth and Reproduction*, P. B. Cronjé (Editor), CAB International, Walingford, UK, pp. 401-408, 2000.

[57] P. B. Cronjé, and E. A. Boomker, “Nutrient-gene interactions: Future potential and applications”, In: *Ruminant Physiology: Digestion, Metabolism, Growth and Reproduction*, P. B. Cronjé (Editor), CAB International, Wallingford, UK, pp. 409-421, 2000.

[58] J. C. Greeff, L. Bouwer, and J. H. Hofmeyr, “Biological efficiency of meat and wool production of seven sheep genotypes”, *Animal Science*, vol. 61, pp. 259-264, 1995.

[59] G. J. Lee, K. J. Thornberry, and A. J. Williams, “The use of thyroxine to reduce average fibre diameter in fleece wool when feed intake is increased”, *Australian Journal of Experimental Agriculture*, vol. 41, pp. 611-617, 2001.

[60] A. J. Williams, “Biological principles”, In: *Australian Sheep and Wool Handbook*, D. J. Cottle (Editor), Inkata Press, Melbourne, Australia, pp. 492- 499, 1991.

[61] G. Lee, and A. Williams, “Relationship of feed intake with cystine availability and wool growth in Merino wethers”, *Australian Journal of Agricultural Research*, vol. 44, pp. 973-991, 1993.

[62] A. Williams, and F. Morley, “Influence of dietary intake and genetic capacity for wool growth on the composition of mid-trunk skin of Merino sheep”, *Australian Journal of Agricultural Research*, vol. 45, pp. 1715-1729, 1994.

[63] P. I. Hynd, and D. G. Masters, “Nutrition and wool growth”, In: *Sheep Nutrition*, M. Freer, and H. Dove (Editors), CAB International, Wallingford, UK, pp. 165-188, 2002.

[64] D. G. Masters, G. Mata, and S. M. Liu, “The influence of type and timing of protein supplementation on wool growth and protein synthesis in the skin of young Merino sheep”, *Australian Journal of Agricultural Research*, vol.50, pp. 497-502, 1999.

[65] C. L. White, P. Young, N. Phillips, and M. Rodehutscord, “The effect of dietary protein source and protected methionine (Lactet) on wool growth and microbial protein synthesis in Merino wethers”, *Australian Journal of Agricultural Research*, vol. 51, pp. 173-184, 2000.

[66] S. M. Liu, G. Mata, H. O'Donoghue, and D. G. Masters, “The influence of live weight, live-weight change and diet on protein synthesis in the skin and skeletal muscle in young Merino sheep”, *British Journal of Nutrition*, vol. 79, pp. 267-274, 1998.

[67] S. M. Liu, and D. G. Masters, “Quantitative analysis of methionine and cysteine requirements for wool production of sheep”, *Animal Science*, vol. 71, pp. 175-185, 2000.

[68] A. E. Huisman, and D. J. Brown, “Genetic parameters for bodyweight, wool, and disease resistance and reproduction traits in Merino sheep. 4. Genetic relationships between and within wool traits”, *Animal Production Science*, vol. 49, pp. 289-296, 2009.

[69] B. A. McGregor, “Influence of nutrition, fibre diameter and fibre length on the fibre curvature of cashmere”, *Australian Journal of Experimental Agriculture*, vol. 43, pp. 1199-1209, 2003.

[70] B. W. B. Holman, and A. E. O. Malau-Aduli, "A review of sheep wool quality traits", *Annual Review and Research in Biology*, vol. 2, pp.1-14, 2012.