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# Cuticle and cortical cell morphology of alpaca and other rare animal fibres

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## ABSTRACT

The null hypothesis of the experiments reported is that the cuticle and cortical morphology of rare animal fibres are similar. The investigation also examined if the productivity and age of alpacas were associated with cuticle morphology and if seasonal nutritional conditions were related to cuticle scale frequency. Cuticle and cortical cell dimensions and ellipticity of the fibre cross section were investigated in 32 samples of cashmere, alpaca, mohair, bison, qiviut and vicuña from various origins. In addition, 24 Peruvian alpaca samples from animals ages 2–6 years and of varying fleece productivity were examined. Cuticle scale frequency, cuticle thickness and cortical cell dimensions (length, diameter, volume and ratio of length to diameter) and ellipticity differed between fibres and cuticle scale frequency also varied with mean fibre diameter. For Peruvian alpaca fleece samples, cuticle scale frequency varied with the age of alpaca and fleece productivity. Fibre ellipticity increased with increasing fibre diameter. Cortical cell length was strongly related to cortical cell diameter. The cuticle scale morphology of these rare animal fibres did not have fixed dimensions. Using cuticle scale morphology as a diagnostic tool to positively identify rare natural animal fibres needs to standardize measurements for fibre diameter but will still be affected by differences in animal productivity.

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## Introduction

The cuticle scales and cortical cells are the two fundamental structural features of animal fibres. As such the outer cuticle and inner cortical cells influence the interactions between the fibres and the environment. The limited evidence available indicates that while wool and other animal fibres have similar basic structural components there are differences in the morphological and chemical composition of these fibres. Cuticle morphology is used to differentiate animal fibres (Wildman, 1954). In recent decades, cuticle scale morphology has been used to identify contaminant fibres particularly in cashmere exported from China (Anonymous, 2010). Wortmann, Wortmann, Arms, and Phan (1988) completed a survey of cuticle scale heights of mohair, cashmere, camel, alpaca, yak and a variety of wools. The wools have a mean scale height of .7–.9  $\mu\text{m}$ , while the values for other animal fibres are around a mean of .3  $\mu\text{m}$  with values of .5  $\mu\text{m}$  relatively rare. Until recently, no explanation could be found to explain why cuticle scale heights within samples of rare animal fibres vary by a factor of 2.5 from .18 to .45  $\mu\text{m}$ . Recently, McGregor and Liu (2017) demonstrated that nutrition, fibre productivity and animal size were related to significant variation in the cuticle scale morphology of cashmere. Thus, it can no longer be assumed that the cuticle morphology of cashmere is a fixed property as it varies with environmental conditions and animal factors.

There have been several studies of cortical cell type in wool, mostly focused on chemical attributes of cortical cells, but fewer studies for other animal fibres (Hudson, 1992; McGregor, 2012a;

Tucker, Hudson, Ozolins, Rivett, & Jones, 1988). Changes in nutrition of sheep and cashmere goats affect the length of cortical cells (Hynd, 1994; McGregor & Liu, 2017) but little is known about the cortical cell morphology for the other animal fibres.

Ellipticity refers to the ratio of the longest to the shortest axes of the fibre cross section. While wool fibres are close to being round in cross section most animal fibres are more elliptical. More circular wool is easier to spin (Martindale, 1945). However, the force required to give the same rate of twist to a fibre (torsional rigidity) is reduced as the ellipticity increases (Lang, 1952). There is little information available on the variation in ellipticity rare animal fibres.

In previous research, it has been shown that the nutrition and productivity of cashmere goats affects cuticle and cortical morphology (McGregor & Liu, 2017). This raises the question of whether cuticle morphology and cortical cells of other rare animal fibres vary to the same extent as was identified for cashmere? More specifically, does the productivity and age of alpacas affect cuticle morphology and are seasonal nutritional conditions related to cuticle scale frequency? The null hypothesis of the experiments reported is that the cuticle and cortical morphology of rare animal fibres are similar.

## Materials and methods

### Fibre samples

A range of 56 fibre samples were examined: alpaca (24 Huacaya fleeces and 5 Peruvian Huacaya tops, 2 Australian Huacaya tops);

cashmere (10 fleeces and 1 top from Australia, 2 fleeces and 3 tops from China, 2 fleeces from Iran); mohair (2 tops from South Africa, 1 top from Australia); bison (1 fleece); qiviut (2 fleeces); vicuña (1 fleece). Alpaca tops were directly sourced from textile companies in Peru and from a top manufacturer in Australia using Australian grown alpaca. Peruvian tops cover the range of royal baby, baby, fine adult and the coarser huarizo fibre. Mohair tops include kid and young goat fibre. Cashmere fleece samples from animals were collected directly by the first author in Iran and China. Australian fleece samples from animals were produced during a cashmere nutrition experiment (McGregor, 1988; McGregor & Liu, 2017) and are included here for comparative purposes. Cashmere and mohair tops were sourced directly from manufacturers. The American bison (*Bison bison*) wool sample came from bison grazed in Victoria, Australia (McGregor, 2012b). Qiviut samples originating from Muskoxen (*Ovibos moschatus*) were provided by Mrs. Colleen White, Palmer, Alaska. One sample came from the tundra, Brooks Range, Alaska and the other from Greenland. The unprocessed vicuña sample was sourced from a manufacturer in Peru. Some of these samples were included in softness and felting research (McGregor, 2014; McGregor & Schlink, 2014). Tops were included in this study to provide representative random samples derived from blended fibre from many animals from the source country.

The alpaca fleece samples originated from at the Research and Development Centre of South American Camelidae, Lachoc, of the National University of Huancavelica. The site is located at 4443 m altitude and 12°53'37"S; 75°05'25"W. Adult female white Huacaya alpaca aged between 1 and 6 years ( $n = 24$ ) from the Lachoc herd were randomly selected from a large collection of samples to cover the range of fleece weights and ages. Fleeces were weighted to the nearest 5 g and sampled prior to shearing in May 2009 from the mid-side site. Mean fleece weight was 2.26 kg (SD 1.29 kg, range 1.16–6.23 kg).

### Measurements of fibre diameter and cuticle scale frequency

All fibre samples were measured for mean fibre diameter (MFD,  $\mu\text{m}$ ) and fibre diameter variation (coefficient of variation (CVD, %)) using the Optical Fibre Diameter Analyser OFDA100 (International Wool Textile Organisation, 2005) with at least 6000 fibre counts.

From alpaca fleece samples, four fibres (non-kemp) were carefully handled to enable measurements of the tip (summer growth), the mid-point and the root (base, autumn/winter growth) of the same fibre to be examined. Samples were washed using 100% ethanol and dried in air for 24 h at 20 °C, then prepared for imaging by a scanning electron microscope (JEOL Neoscope JCM-5000). Fibres were gold-coated and the mounted sections of the fibre were placed in high vacuum condition and examined under X 800 magnification and beam strength of 10 kV. For each section of a fibre, four measurements of the cuticle scale frequency were made as number of scales/100  $\mu\text{m}$  length. The fibre diameter along the length of the fibre where each cuticle scale measurement was made was measured in four places. Mean values for each fibre and for each sample were determined. For the other fleece samples, a similar process was followed to obtain mean values for eight fibres per sample.

### Cuticle thickness and fibre cross-sectional shape

A bundle of fibres from each sample was fixed in polyester resin and slices were cut after curing using a microtome. The cross sections were examined using an Olympus BX51 microscope fitted with an Optronics digital camera. Fibres were manually measured at X 300 magnification. The longest (major) and the shortest (minor) axes of the fibres were measured using the UTSCA Image Tool for Windows v3.00. Guard hairs, identified as having a mean fibre diameter > 50  $\mu\text{m}$  and possessing medulla, were omitted from the analysis although fine medullated fibres were retained in the datasets for mohair, alpaca and qiviut. The fibre ellipticity was determined as: ratio of the fibre diameter = longest axis/shortest axis.

### Cortical cell dimensions

Cortical cells were obtained from 8 to 15 fibres per sample by chemically and mechanically extraction for a total of 271 fibres sampled. Fibre samples were cleaned by 100% ethanol and dried in air for 24 h at 20 °C. Fibre snippets of 2 mm cut from cleaned samples were pre-treated in 98% sulphuric acid for 5 min, then milled in a grinding mortar until all the intercellular protein between cortical and cuticle cells dissolved. The droplet of fibre slurry was placed on a glass slide and dried for 24 h at 20 °C.

The microscope used for cuticle thickness measurements was used for cortical dimensions with a polarizing filter to provide optimum contrast for images that were photographed at X 300 magnification. For each field of view the length and greatest width of undamaged cortical cells were manually measured to the nearest 10 nm. More than 10,000 individual cortical cells were measured. Cortical cell volume was calculated as if the cortical cells were two cones joined at the widest and middle point:  $\pi/3 \times (\text{width}/2)^2 \times \text{length}$ . The ratio of cortical cell length to cortical cell diameter was determined as: LD ratio = length/width.

### Statistical analysis

For the analysis of cuticle scale frequency and cortical cell measurements the mean data for each fibre was used as replicates. For cuticle scale thickness and ellipticity each measurement represented a different sample and was treated as a replicate. Differences between species fibre type were determined using REML (Payne, 2013). Multiple linear regression analysis was used to quantify variance accounted by different variates. As there was no systematic difference between tops and fleece samples ( $p > .05$ ) these samples were combined for each species fibre.

For the alpaca study, mean data for each section of each fibre was treated as a separate replicate for analysis as each had a different fibre diameter. This provided 24 fleeces  $\times$  3 sites along each fibre = 72 degrees of freedom for the analyses. Five fibre sections were lost and one mean value was identified as an outlier and excluded. Parsimonious general linear models with normal errors were developed in a forward stepwise manner using GenStat 15.2 for Windows (Payne, 2013) to determine the relationships between cuticle scale frequency and cortical cell measurements, with other objective information, and with terms being added or rejected on the basis of  $F$ -tests ( $p < .05$ ; Payne, 2013). For significant variates, the square of the variate and the product of significant variates were tested for significance. Once

the final models were determined, the marginal significance of each term in the final model was determined and the marginal significance of rejected terms was also determined. The residual standard deviation of regressions (r.s.d.) and multiple correlation coefficient ( $R$ ) were determined.

## Results

The range in MFD for the different fibre types were: alpaca, 21.9–32.4  $\mu\text{m}$ ; cashmere, 14.4–19.3  $\mu\text{m}$ ; mohair, 29.1–33.5  $\mu\text{m}$ ; bison, 15.8  $\mu\text{m}$ ; qiviut, 14.3–22.4  $\mu\text{m}$ ; vicuña, 13.2  $\mu\text{m}$ .

### Cuticle scale frequency

There were significant differences between the cuticle scale frequency of the different fibres (Table 1). In order of rank, vicuña had the highest frequency which differed from alpaca and bison, followed by cashmere and qiviut and mohair exhibited the lowest cuticle scale frequency. Fibre type explained 33% of the variance in cuticle scale frequency (r.s.d. 1.56;  $p = 2.8 \times 10^{-16}$ ) and MFD alone explained 12.7% of the variance in cuticle scale frequency. The most parsimonious model contained both fibre type and MFD and explained 50.3% of the variance in cuticle scale frequency (r.s.d. 1.34;  $p = 1.0 \times 10^{-24}$ ). Generally, for each 1  $\mu\text{m}$  increase in MFD, cuticle scale frequency declined .15/100  $\mu\text{m}$  (SE .022). However, with cashmere, cuticle scale frequency declined between .23 and .50/100  $\mu\text{m}$  with each 1  $\mu\text{m}$  increase in MFD, respectively, for Australian and Chinese cashmères.

**Table 1.** Mean, standard deviation (SD) and ranges for cuticle scale frequency, cuticle thickness and fibre ellipticity (ratio of fibre diameter: longest axis/shortest axis) for cashmere, mohair, qiviut, alpaca, vicuña and bison fibre.

Variables	Mean	SD	Minimum	Maximum	$n$
<i>Cuticle scale frequency (/100 <math>\mu\text{m}</math>; <math>n = 217</math> fibres)</i>					
Chinese cashmere	7.5 <sup>c</sup>	1.58	5	10	24
Iranian cashmere	7.2 <sup>c</sup>	1.04	5	9	21
Australian cashmere	6.9 <sup>c</sup>	1.60	4	13	91
Mohair	5.4 <sup>d</sup>	1.50	4	9	18
Qiviut	6.9 <sup>c</sup>	1.98	5	11	13
Bison	9.2 <sup>b</sup>	1.72	6	11	6
Australian alpaca	9.7 <sup>b</sup>	1.03	8	11	6
Peruvian alpaca	8.8 <sup>b</sup>	1.68	6	12	23
Peruvian vicuña	11.5 <sup>a</sup>	1.38	9	13	6
<i>Cuticle thickness (nm; <math>n = 646</math>)</i>					
Chinese cashmere	430 <sup>b</sup>	97	260	658	65
Iranian cashmere	430 <sup>b</sup>	138	184	795	72
Australian cashmere	424 <sup>b</sup>	124	168	769	296
Mohair	554 <sup>a</sup>	147	282	762	32
Qiviut	366 <sup>cd</sup>	105	195	532	28
Bison	394 <sup>bcd</sup>	87	261	562	21
Australian alpaca	394 <sup>bc</sup>	130	240	812	47
Peruvian alpaca	335 <sup>d</sup>	72	204	522	63
Peruvian vicuña	247 <sup>e</sup>	98	127	508	22
<i>Ellipticity (<math>n = 1559</math>)</i>					
Chinese cashmere	1.18 <sup>a</sup>	.115	1.00	2.01	211
Iranian cashmere	1.21 <sup>ab</sup>	.148	1.00	1.87	160
Australian cashmere	1.19 <sup>a</sup>	.138	1.00	1.89	625
Mohair	1.22 <sup>b</sup>	.186	1.00	2.40	186
Qiviut	1.32 <sup>de</sup>	.209	1.00	1.95	69
Bison	1.24 <sup>bc</sup>	.152	1.00	1.70	66
Australian alpaca	1.25 <sup>bc</sup>	.175	1.01	2.06	76
Peruvian alpaca	1.34 <sup>e</sup>	.254	1.00	2.28	140
Peruvian vicuña	1.29 <sup>de</sup>	.234	1.03	2.22	26

Notes: Within measurements, mean values with different superscripts differ at  $p = 0.05$ .

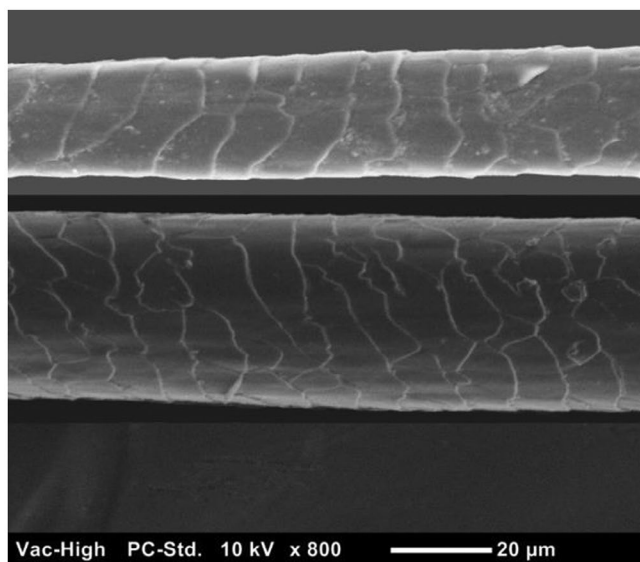
### Productivity effects on cuticle scale frequency of alpaca

MFD for individual alpaca fibres was 22.2  $\mu\text{m}$  (SD 7.01  $\mu\text{m}$ , range 12.9–61.4  $\mu\text{m}$ ). Mean cuticle scale frequency was 9.9/100  $\mu\text{m}$  (SD 1.14; range of 7.0–14.7/100  $\mu\text{m}$ ) indicating a coefficient of variation was 11.5% and a variation by a factor of 2.1. Mean fleece weight was 2.71 kg (range 1.37–7.21 kg).

MFD accounted for 19.2% of the variance in cuticle scale frequency ( $p < .001$ ) with cuticle scale frequency increasing .076 ( $\pm 0.018$ ) for each 1  $\mu\text{m}$  increase in MFD. Age of alpaca accounted for 33.0% of the variance in cuticle scale frequency ( $p < .001$ ). Fleece weight added significantly to the linear relationship with cuticle scale frequency but adding the section of the fibre (tip, middle, base) to a regression was not significant in explaining more of the variance. The most parsimonious model for cuticle scale frequency had terms for age of alpaca ( $p = 2.6 \times 10^{-10}$ ) and fleece weight ( $p = 2.2 \times 10^{-6}$ ). This model accounted for 52% of the variance (r.s.d. .69). The effects of variation in the significant terms in the model are shown in Table 2. Compared with age 1 and 2, increasing age of alpacas resulted in an increase in cuticle scale frequency, particularly at ages 5 and 6. Additionally, increasing greasy fleece weight resulted in a decline in cuticle scale frequency. Figure 1 exhibits two SEM micrographs illustrating the appearance and variation of cuticle scale frequency from alpaca grown by a 2-year-old and a 6-year-old alpaca. The effects

**Table 2.** Regression coefficients and their standard error for the relationship between alpaca cuticle scale frequency and the age of alpaca (years) and greasy fleece weight (kg),  $n = 78$ . The regression constant is for 1-year-old alpacas.

Parameter	Regression constant	Coefficient estimate	SE	$p$ -value
Constant	10.65		.222	<.001
Greasy fleece weight		-.504	.0969	<.001
Age 2		-.22	.258	.405
Age 3		.72	.316	.025
Age 4		.79	.330	.020
Age 5		2.03	.453	<.001
Age 6		2.89	.332	<.001



**Figure 1.** The surface of alpaca fibres showing the cuticle scales.

Notes: Top fibre grown by 2-year-old alpaca, producing 2.20 kg fleece of fibre diameter 21.7  $\mu\text{m}$  and 9.5 cuticle scales/100  $\mu\text{m}$ . The lower fibre grown by 6-year-old alpaca producing 1.65 kg fleece of fibre diameter 38.8  $\mu\text{m}$  and 12.0 cuticle scales/100  $\mu\text{m}$ .

of changes in alpaca age and greasy fleece weight are illustrated in Figure 2.

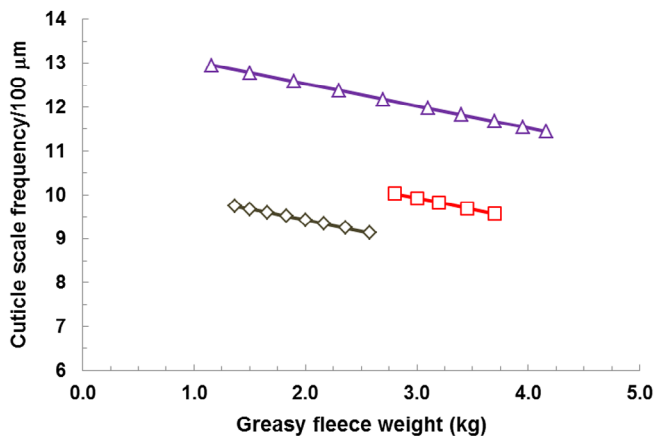
In the most parsimonious model MFD was not significant once age was included in the model. The correlation coefficient between age and MFD was .71 ( $p < .001$ ). Effectively age accounted for much of the variation in MFD as MFD increased from a mean of 18.9  $\mu\text{m}$  at age 1, to 22.7  $\mu\text{m}$  at age 2, to 33.9  $\mu\text{m}$  at age 6.

### Cuticle thickness and ellipticity

There were significant differences between fibre type in cuticle thickness ( $F$ -value 13.66;  $p < .001$ ; Table 1). The mean cuticle thickness in cashmere was 424–430 nm and the range of 168–795 nm indicated a variation by a factor of 5 times (Table 1). The cuticle thickness of mohair 554 nm (range varied by a factor of 2.7

times) was significantly higher than all other fibres. The cuticle thickness of Peruvian vicuña (247 nm) was significantly lower than all other fibres including alpaca. Qiviut and bison had similar cuticle thickness of 366 and 394 nm, respectively (Table 1). The diameter of the fibre was not related to cuticle thickness.

There were significant differences between fibre type in ellipticity ( $F$ -value 15.28;  $p < .001$ ; Table 1). For ellipticity, cashmere was the least elliptical with a mean ellipticity of 1.18–1.21, while Peruvian alpaca, vicuña and qiviut were the most elliptical fibres with a mean ellipticity of 1.29–1.34 (Table 1). All fibre samples contained fibre sections with a circular cross section (ellipticity = 1.0) and also fibres with highly elliptical cross sections (ellipticity up to and greater than 1.70, Table 1). Figure 3 provides SEM images of the cross section of some cashmere and mohair fibres. Ellipticity increased by .006 (SE .0010) for each 1  $\mu\text{m}$  increase in the average fibre diameter of the cross section ( $F$ -value 32.17;  $p < .001$ ).



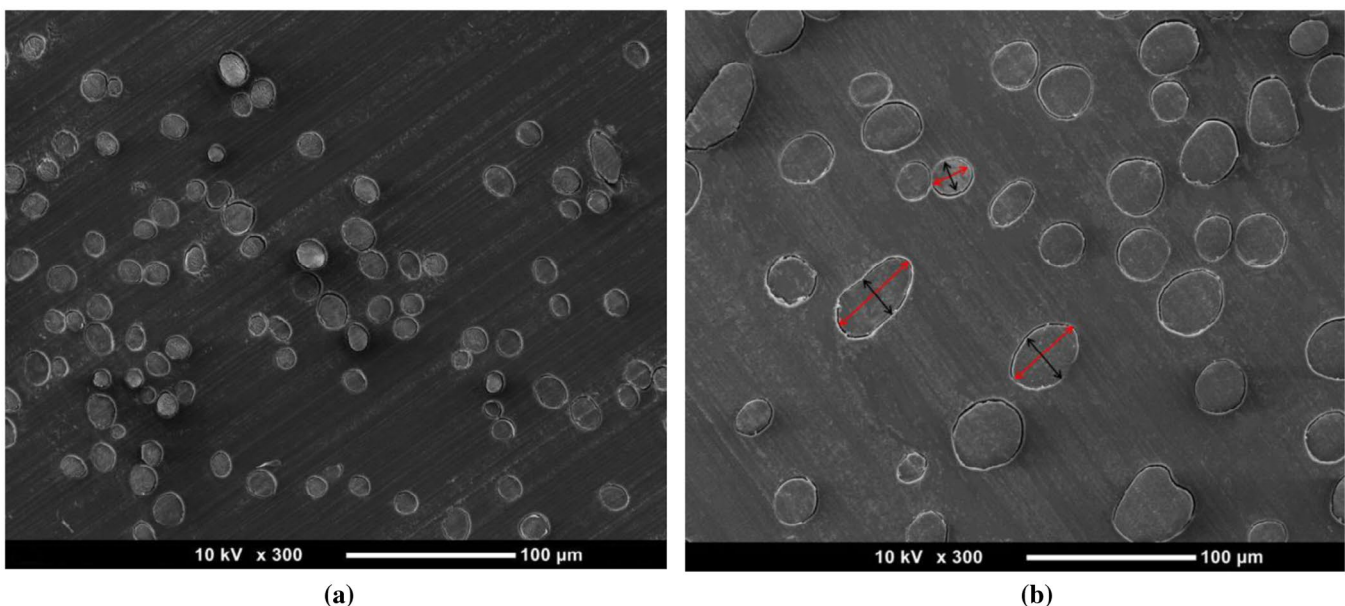
**Figure 2.** The predicted main effects of alpaca age and greasy fleece weight on the frequency of cuticle scales on Peruvian alpaca shown for the range of greasy fleece weight in the data-set.

Notes: Symbols for ages: 2 years (♦); 4 years (□); 6 years (△).

### Cortical cell properties

The mean cortical cell length, diameter, volume and LD ratio for samples are shown in Table 3. Cortical cell length showed considerable variation with CV ranges of 15–27%. For alpaca, the higher CV range was related to one sample with mean length of 73  $\mu\text{m}$  and cells up to 135  $\mu\text{m}$  (Figure 4). Excluding this sample provided alpaca with a similar CV to other fibres. Cortical cell diameter showed less variation with CV range of 9–21% with means of 4.5–4.9  $\mu\text{m}$ . Cortical cell volumes ranged from vicuña 230  $\mu\text{m}^3$  to alpaca 364  $\mu\text{m}^3$ .

Cortical cell diameter ( $p = 1.3 \times 10^{-7}$ ) and fibre type ( $p = .00074$ ) explained 81.0% of the variation in cortical cell length (r.s.d. 2.98; Figure 4). The variation in the diameter of cortical cells alone explained 57% of the variance in cortical cell length. Regression constants indicated that cortical cell length increased 12.8  $\mu\text{m}$  / 1  $\mu\text{m}$  increase in cortical cell diameter (SE 1.57). Compared with the other fibres tested, qiviut cortical cells

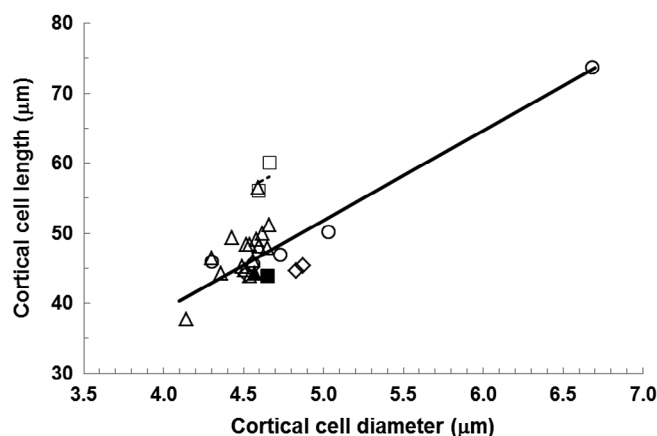


**Figure 3.** Scanning electron microscope images of the cross section of (a) cashmere and (b) mohair fibres.

Note: For mohair, examples of the longest and the shortest axes of some fibres are shown.

**Table 3.** Mean, standard deviation (SD), coefficient of variation (CV) and ranges for cortical cell dimensions and ratio of length to diameter for samples of alpaca, cashmere, mohair, bison, qiviut and vicuña. For length and diameter, the values are based on all measurements. For volume and ratio means and SD the values are based on mean fibre values.

Variables	Mean	SD	CV (%)	Minimum	Maximum
<b>Cortical cell length</b> ( $\mu\text{m}$ ; $n = 10,125$ )					
Alpaca	50.5	13.91	27.5	14.9	135.2
Cashmere	47.5	8.74	18.3	16.7	88.7
Mohair	44.6	8.25	18.6	17.5	83.1
Qiviut	57.3	11.53	20.1	24.7	95.6
Bison	43.6	6.99	16.1	26.6	63.6
Vicuña	42.5	6.48	15.3	27.5	70.9
<b>Cortical cell diameter</b> ( $\mu\text{m}$ )					
Alpaca	4.9	1.04	21.2	1.0	11.4
Cashmere	4.5	.65	14.4	1.5	8.3
Mohair	4.7	.64	13.6	2.7	7.9
Qiviut	4.6	.59	12.8	2.9	6.6
Bison	4.7	.63	13.4	2.9	6.3
Vicuña	4.6	.42	9.1	3.7	6.8
<b>Cortical cell volume</b> ( $\mu\text{m}^3$ )					
Alpaca	364	224.9		196	1104
Cashmere	254	38.4		137	342
Mohair	261	29.6		215	315
Qiviut	324	35.1		245	384
Bison	248	14.9		231	271
Vicuña	230	27.7		195	276
<b>Cortical cell ratio length:diameter</b>					
Alpaca	10.3	.81		8.5	11.9
Cashmere	10.5	.91		8.4	13.2
Mohair	9.5	.63		7.8	10.5
Qiviut	12.5	1.02		10.1	13.9
Bison	9.5	.67		8.4	10.9
Vicuña	9.2	.57		8.5	10.0



**Figure 4.** Lines of best fit showing the relationships between cortical cell length and diameter for various animal fibres.

Notes: Symbols:  $\Delta$ , cashmere;  $\circ$ , alpaca;  $\square$ , qiviut (dotted line);  $\blacksquare$ , bison;  $\diamond$ , mohair;  $\blacktriangle$ , vicuña.

were significantly longer ( $10.6 \mu\text{m}$ ;  $p < .001$ ) relative to their diameter. There was no significant association between the MFD or the CVD of samples and cortical cell length ( $p > .1$ ). Cortical cell diameter and volume were not related to fibre type in the samples tested. The alpaca sample with the largest cortical cell diameter appears to exert high leverage on the regression (Figure 4), but as omission of this sample makes little change to the regression, the data point has been retained in the analysis.

LD was best predicted by a model with cortical cell length accounting for 84.0% of the variance, and including MFD ( $p = .014$ ) increased variance accounted for to 87.9% (r.s.d. .338). The ratio of cortical cell length to cortical cell diameter (LD) increased .19/1  $\mu\text{m}$  (SE .0149) increase in cortical cell length ( $p = 1.5 \times 10^{-11}$ ) and declined by .03 (SE .011)/1  $\mu\text{m}$  increase in MFD. Fibre type, CVD and cortical cell diameter were not significant in explaining LD.

## Discussion

### Cuticle scale frequency

There was a large range in the cuticle scale frequency both within and between species fibre types, in accord with previous studies. This study provided new data on qiviut and bison fibre, as well as, accounting for a significant proportion of the variation in alpaca cuticle scale frequency with alpaca age and fleece weight. Cuticle scale frequency also declined as MFD increased, which has been previously reported in cashmere (Yang, Fu, Hong, & Wang, 2005) where cuticle scale frequency of a wide sample of Chinese cashmere declined and the ratio of fibre diameter to cuticle scale length increased as fibre diameter increased.

The cuticle scale frequency of the bison fibres were higher than most of the other fibres, perhaps a result of relatively low rates of fibre growth (McGregor, 2012b). Qiviut had a similar cuticle scale frequency compared with the samples of cashmere. The cuticle scale frequency of mohair was at the lower end of values reported by Wildman (1954), Teasdale (1988) and Phan, Wortmann, Wortmann, and Arns (1988), respectively, 3.5–7.5, 5.5–7 and 6–7/100  $\mu\text{m}$ . The value for vicuña was similar to the 11 scales/100  $\mu\text{m}$  reported by Phan et al. (1988).

A change in the biosynthesis rate of keratin appears to affect cuticle scale production per unit length of wool (Rougeot, 1965) and cashmere (McGregor & Liu, 2017). The effect of fibre diameter upon cuticle scale frequency may relate to variations in nutritional status, but it also implies that larger fibres grown in primary skin follicles will differ from finer fibres grown in secondary skin follicles. Additionally, as skin follicle density varies over the body of animals, so will MFD and therefore cuticle morphology. Thus, within any sample of animal fibre there will be a bivariate distribution in cuticle scale frequency, which some authors have illustrated with concentric rings based on the probability of occurrence (Phan et al., 1988; Teasdale, 1988).

### Cuticle scale frequency of Peruvian alpaca fleece samples

Both the age of alpacas and the productivity of Peruvian alpaca affected the cuticle scale frequency of the samples. No further effect of MFD or section of fibre was detected, despite the observation that MFD alone accounted for 19% of the variance in cuticle scale frequency. These results indicate that the cuticle scale frequency of alpaca is not a fixed characteristic and varies in a previously unexplained manner with the age of animals.

It may be easier to explain the effect of increasing greasy fleece weight as a result of greater fibre length growth per unit time, thus cuticle scale frequency declines with increasing greasy fleece weight. However, age was also related to increases in MFD. Age of alpacas has previously been associated with the general tendency

for older alpacas to produce coarser fibres on average (McGregor & Butler, 2004). It could be that other effects are occurring in the skin follicle such that the skin follicle bulb may only be able to produce a certain amount of keratin material per unit time for the fibre shaft. Thus, as the fibre diameter increases so the length growth rate is proportionally reduced. For example, in the present study the cross-sectional area of the fibre at 6 years of age was over three times that at 1 year of age, so unless keratin production was over three times higher at 6 years of age compared with 1 year of age length growth would be reduced and cuticle scale frequency would be greater in older alpacas compared with younger animals. Teasdale (1988) also reported an apparent effect of age of Angora goat on the cuticle scale frequency of mohair indicating that mohair grown by older goats had a higher cuticle scale frequency compared with mohair grown by younger goats.

Cuticle scale characteristics of alpaca fibre have been reported by Wortmann et al. (1988), but they did not distinguish between Huacaya and Suri alpaca. Suri alpaca scale edge frequency for fibre ranging in MFD of 24.8–28.2  $\mu\text{m}$  and originating from four countries of origin ranged from 8.0 to 10.3/100  $\mu\text{m}$  (Wang, Wang, & Liu, 2003). Valbonesi, Cristofanelli, Pierdominici, Gonzales, and Antonini (2010) differentiated Suri alpaca (MFD 24.4  $\mu\text{m}$ ) from Huacaya fibre (MFD 27.4  $\mu\text{m}$ ) and llama (chaku woolly, MFD 29.6  $\mu\text{m}$ ) fibre on the basis of cuticle scales. Cuticle scale height did not differ between samples of llama, Huacaya and Suri fibre being, respectively, 400, 520, 470 nm. Cuticle scale frequency differed between Suri fibre and Huacaya and llama fibre and the relationship between cuticle scale frequencies differed with MFD of both Suri and llama fibre but not Huacaya fibre. For Huacaya, the cuticle scale frequency was 9.1. For Suri, the cuticle scale frequency increased from 7.5 at 20  $\mu\text{m}$  by .29 for every 10  $\mu\text{m}$  increase in MFD and for llama it increased from about 9.2 at 20  $\mu\text{m}$  by .54 for every 10  $\mu\text{m}$  increase in MFD.

### Cuticle scale thickness

Cuticle thickness varied with fibre type, with mohair having the highest thickness and vicuña the lowest cuticle thickness. The cuticle thickness values for mohair, cashmere and alpaca are similar to the cuticle scale heights reported by Phan et al. (1988). This report extends that information to include bison, qiviut and differentiates between alpaca sourced from Peru and Australia. Wortmann et al. (1988) found little difference in scale height between mohair, cashmere, alpaca, yak and camel from different producing regions, with the range for cashmere of about 180–450 nm and averages about 300 nm. Investigating a range of lustre wools and mohair from different origins, Weideman, Gee, Hunter, and Turpie (1988) found that there was an overlap in cuticle scale height distributions between mohair and wool. Mean scale height for mohair samples ranged between 470 and 570 nm with 95% confidence limits for samples ranging between 360–600 nm and 390–750 nm. The results also detected a difference between the cuticle thickness of alpaca grown in Peru and Australia, although this may be a sampling issue.

No effect of MFD on cuticle scale thickness was detected although previously with Chinese cashmere Yang et al. (2005) found cuticle scale height averaged 340 nm in fibres with a MFD < 18.0  $\mu\text{m}$  and 360 nm in fibres with a MFD  $\geq$  18.0  $\mu\text{m}$ . Manipulating the nutrition of cashmere goats has been shown to affect cuticle thickness (McGregor & Liu, 2017).

### Ellipticity

There were differences in the ellipticity of the fibres tested, with cashmere being the least elliptical and Peruvian alpaca, qiviut and vicuña the most elliptical. Fibre ellipticity of Peruvian alpaca has been reported to increase as MFD increases from a ratio of 1.15 at 22  $\mu\text{m}$  to 1.28 at 32  $\mu\text{m}$  which means alpaca was more circular than wool at 22  $\mu\text{m}$  but more elliptical than wool at 30  $\mu\text{m}$  (Villarroel, 1959). Large differences in axial diameter of these fibres (high ellipticity) will affect the bending properties of the fibres and may contribute to the relative lower softness of alpaca compared with other species fibre (McGregor, 2014). Lower cuticle thickness and the higher ellipticity of alpaca (Table 3) may contribute to greater softness compared with other fibres. Recent investigations showed that the ellipticity of cashmere was affected by nutritional manipulation and MFD and lower cuticle thickness was associated with lower ellipticity (McGregor & Liu, 2017).

### Cortical cell morphology

There was a large relative range in the size of cortical cell length, diameter and volume (Table 3). However, the relative shape of cortical cells was predictable as cortical cell length was strongly related to cortical cell diameter although the ratio length:diameter increased as length increased. Generally, the cortical dimensions of these rare animal fibres were similar with the exception that qiviut had longer cortical cells exhibiting a higher LD ratio leading to cortical cells with a relatively greater volume compared with cashmere, mohair and vicuña. Qiviut is a relatively short downy fibre with typical down lengths of 4.5–6 cm although there are reports of down lengths up to 8 cm (Rowell et al., 2001). In Merino sheep, changes in nutrition leading to longer cortical cells are associated with longer wool fibres (Hynd, 1994). Given that Muskoxen graze in tundra conditions mainly on lichen, the finding that qiviut has very long cortical cells compared with the other fibres suggests the follicular determinants of cortical length may differ from the other species studied.

In the present work, MFD had no effect on cortical cell length although in the study of Brady and Wang (2005), using a wide range of wool samples, finer wool had shorter cortical cells compared with coarser wool. Previously, it was shown in a controlled experiment on manipulating the nutrition of cashmere goats, that higher levels of nutrition resulted in longer cortical cells with greater diameter, volume and a higher LD ratio compared with cashmere grown by goats in restricted nutrition treatments (McGregor & Liu, 2017). Thus, the results from various studies indicate that the internal physical structure of rare animal fibres maintain their relative dimensions but factors affecting cortical length, such as nutrition, result in longer or shorter cortical cells.

Most of the alpaca fibre grown in Peru is harvested from the nutritionally restricted Altiplano region and at intervals of 18–24 months. It is likely that the alpaca sample with the longest cortical cell length in Figure 4 was grown in the Altiplano. It is not known how nutritionally restricted alpacas may grow the longest cortical cells. It is possible that this result is explained by the investigation of White and Henderson (1973) into New Zealand Romney wool. New Zealand Romney sheep and alpacas have similar growth cycles whereby nutritional restrictions occur during the winter half year when day length is also reduced. In

the study of White and Henderson (1973), cortical cell length and diameter increased when Romney wool growth rate was declining, associated with a decline in follicle cell mitotic activity and reduced lengthwise cellular compression. Thus, White and Henderson (1973) postulated larger cortical cell size in winter. Such an explanation may also be relevant to the finding that qiviut cortical length measurements were longer than the cortical cell length of the other fibres reported in the present work.

## Implications and conclusion

The results show that the cuticle and cortical cell morphology of cashmere, alpaca, mohair, bison, qiviut and vicuña exhibit a large range in dimensions. The results also show that cuticle scale frequency and cortical cell morphology of the tested samples varied significantly between fibres from the different species, and cuticle scale frequency was affected by fibre diameter. With alpaca, cuticle morphology varied with age of alpaca and animal productivity. Thus, naturally grown alpaca fibres exhibit significant variation in cuticle scale frequency. It would appear that the cuticle scale morphology of these rare animal fibres do not have fixed dimensions. It should therefore be expected that animal fibres produced in very different production systems, which have varying nutritional provisions, from animals of different productivity will have an inherent range in cuticle and cortical cell morphology. Using cuticle scale morphology as a diagnostic tool to positively identify rare natural animal fibres needs to standardize measurements for fibre diameter but will still be affected by differences in animal productivity.

There were also some important differences between the cuticle thickness and the ellipticity of different rare animal fibres which may explain variation in perceived and measured softness between these fibres and when compared with wool. Ellipticity increased with mean fibre diameter. The relative shape of cortical cells was predictable as the length was strongly related to the diameter of cortical cells.

The consequences of these variations in cuticle scale frequency and therefore cuticle scale size will be variation in: surface friction characteristics; surface lustre attributes; differences in fibre cohesion during processing; and different felting and wear properties of textiles (Hunter, 1993; Simpson & Crawshaw, 2002). The superior textile properties of baby alpaca may be related to the lower cuticle scale frequency compared with adult alpaca identified in this study.

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## References

- Anonymous. (2010). Cashmere and Camel Hair Manufacturers Institute. Retrieved December 15, 2010, from <https://www.cashmere.org/cm/index.php>.
- Brady, P. R., & Wang, X. (2005). Cashmere and wool cortical cells. *Proceedings of the 3rd International Cashmere Determination Technique Symposium*, 149–158. China National Cashmere Products Engineering and Technical Centre and China Inner Mongolia Erdos Cashmere Group Corporation, China.
- Hudson, A. H. F. (1992). *The chemistry and morphology of goat fibres* (PhD thesis). Deakin University, Geelong.
- Hunter, L. (1993). *Mohair: A review of its properties, processing and applications*. Port Elizabeth: CSIR.
- Hynd, P. I. (1994). Follicular determinants of the length and diameter of wool fibres. 1. Comparison of sheep differing in fibre length/diameter ratio at two levels of nutrition. *Australian Journal of Agricultural Research*, 45, 1137–1147.
- International Wool Textile Organisation. (2005). *Measurement of the mean and distribution of fibre diameter of wool using an optical fibre diameter analyser (OFDA)*. IWTO -47. Brussels: Author.
- Lang, W. (1952). Wool fibre contour: Its significance to the mechanical properties of the fibre. *Journal of the Textile Institute*, 43, P245–P251.
- Martindale, J. G. (1945). 4—A new method of measuring the irregularity of yarns with some observations on the origin of irregularities in worsted slivers and yarns. *Journal of the Textile Institute*, 36, T35–T47.
- McGregor, B. A. (1988). Effects of different nutritional regimens on the productivity of Australian cashmere goats and the partitioning of nutrients between cashmere and hair growth. *Australian Journal of Experimental Agriculture*, 28, 459–467.
- McGregor, B. A. (2012a). *Properties, processing and performance of rare and natural fibres: A review and interpretation of existing research results* (RIRDC Research Report No. 11/150, pp. xii + 103). Barton, ACT: RIRDC.
- McGregor, B. A. (2012b). Production, properties and processing of American bison (*Bison bison*) wool grown in southern Australia. *Animal Production Science*, 57, 431–435.
- McGregor, B. A. (2014). Variation in the softness and fibre curvature of cashmere, alpaca, mohair and other rare animal fibres. *Journal of the Textile Institute*, 105, 597–608.
- McGregor, B. A., & Butler, K. L. (2004). Sources of variation in fibre diameter attributes of Australian alpacas and implications for fleece evaluation and animal selection. *Australian Journal of Agricultural Research*, 55, 433–442.
- McGregor, B. A., & Liu, X. (2017). Cuticle and cortical cell morphology and the ellipticity of cashmere are affected by nutrition of goats. *The Journal of the Textile Institute*, 108, 1739–1746.
- McGregor, B. A., & Schlink, A. C. (2014). Feltability of cashmere and other rare animal fibres and the effects of nutrition and blending with wool on cashmere feltability. *The Journal of the Textile Institute*, 105, 927–937.
- Payne, R. W. (Ed.). (2013). *The guide to GenStat®; Release 15. Part 2: Statistics*. Hertfordshire: VSN International.
- Phan, K. H., Wortmann, F. J., Wortmann, G., & Arns, W. (1988). Characterization of specialty fibre by scanning electron microscopy. Vol. 103. In *Proceedings of the 1st International Symposium on Speciality Animal Fibres* (pp. 137–162). Aachen: Schriftenreihe der Deutsches Wollforschungsinstitutet.
- Rougeot, J. (1965). The effects of thyroid hormones on the morphology of the wool cuticle. In A. G. Lyne & B. F. Short (Eds.), *Biology of the skin and hair growth* (pp. 625–640). Sydney: Angus & Robertson.
- Rowell, J. E., Lupton, C. J., Robertson, M. A., Pfeiffer, F. A., Nagy, J. A., & White, R. G. (2001). Fiber characteristics of qiviut and guard hair from wild muskoxen (*Ovibos moschatus*). *Journal of Animal Science*, 79, 1670–1674.
- Simpson, S. W. S., & Crawshaw, G. H. (Eds.). (2002). *Wool: Science and technology*. Cambridge: Woodhead Publishing; Boca Raton, FL: CRC Press.
- Teasdale, D. C. (1988). Multivariate analysis in fibre characterisation and identification. Vol. 103. In *Proceedings of the 1st International Symposium on Speciality Animal Fibres* (pp. 23–38). Aachen: Schriftenreihe der Deutsches Wollforschungsinstitutet.



- Tucker, D. J., Hudson, A. H. F., Ozolins, G. C., Rivett, D. E., & Jones, L. N. (1988). Some aspects of the structure and composition of specialty animal fibres. Vol. 103. In *Proceedings of the 1st International Symposium on Specialty Animal Fibers* (pp. 71–103). Aachen: Schriftenreihe der Deutsches Wollforschungsinstitut.
- Valbonesi, A., Cristofanelli, S., Pierdominici, F., Gonzales, M., & Antonini, M. (2010). Comparison of fiber and cuticular attributes of alpaca and llama fleeces. *Textile Research Journal*, 80, 344–353.
- Villaruel, J. L. (1959). *A study of alpaca fibre* (MSc thesis). University of New South Wales, Sydney.
- Wang, X., Wang, L., & Liu, X. (2003). *The quality and processing performance of alpaca fibres* (RIRDC Publication No. 03/128). Canberra, ACT: RIRDC.
- Weideman, E., Gee, E., Hunter, L., & Turpie, D. W. F. (1988). Scale height distributions of a wide range of mohair and wool lots. Vol. 103. In *Proceedings of the 1st International Symposium on Specialty Animal Fibers* (pp. 189–204). Aachen: Schriftenreihe des Deutschen Wollforschungsinstitutes.
- White, D. H., & Henderson, A. E. (1973). Wool production of Romney ewes and its relationship to cortical cell size. *New Zealand Journal of Agricultural Research*, 16, 539–544.
- Wildman, A. B. (1954). *The microscopy of animal textile fibres*. Leeds: WIRA.
- Wortmann, F. J., Wortmann, G., Arms, W., & Phan, K.-H. (1988). Analysis of specialty fiber/wool blends by means of scanning electron microscopy (SEM). Vol. 103. In *Proceedings of the 1st International Symposium on Specialty Animal Fibers* (pp. 163–188). Aachen: Schriftenreihe des Deutschen Wollforschungsinstitutes.
- Yang, G., Fu, Y., Hong, X., & Wang, C. (2005). Discussion on cashmere fiber identification technique by SEM and LM. In *Proceedings of the 3rd International Cashmere Determination Technique Symposium* (pp. 189–205). China: China National Cashmere Products Engineering and Technical Centre and China Inner Mongolia Erdos Cashmere Group Corporation.