Changes in live weight and fleece characteristics during the lifetime of three breeds of New Zealand feral sheep that differ in fleece type

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Abstract

Live weight after joining and nine fleece characteristics were recorded throughout the lifetime of flocks of Hokonui, Campbell Island and Raglan sheep grazing at Whatawhata and Winchmore Research Centres between 1991 and 2004. The wool characteristics were measured in 585 individual wool samples collected at shearing from 90 breeding ewes sampled between one year of age and up to 12 years of age. Data on live weight, fleece weight, staple length, mean and variability of fibre diameter, fibre curvature, crimping and core bulk were analysed after adjustment for effects of grazing location and reproductive performance during the previous year. The three flocks differed in all measured characteristics, with all except live weight, mean fibre curvature and core bulk exhibiting a significant flock by age interaction. Live weight attained a maximum at six years of age, while greasy fleece weight and staple length decreased after two years of age. Core bulk decreased after three years of age. Fibre curvature decreased and time to form a crimp increased throughout the sheep's life. Fibre diameter variability between and along fibres showed a variable age response between flocks. The three feral flocks exhibited a different age response to continuously farmed breeds.

Keywords: fleece characteristics; age effects; Hokonui; Campbell Island; Raglan

Introduction

Although sheep anecdotally have a life expectancy of 10 to 12 years, this requires healthy incisor teeth to maintain adequate food intake. As a consequence of tooth wear, which can vary between regions, it is common commercial practice in New Zealand to cull all breeding ewes by five or six years of age, at which time their health and associated productivity may have begun to decline (Bruère & West 1993).

While most wool characteristics are known to change with age (Sumner & Bigham 1993), modern instruments are now able to measure more objective wool characteristics than was possible in earlier studies reported for medium-wool Merino ewes in Australia (Brown et al. 1966) and Perendale ewes in New Zealand (Sumner & Dick 1997).

When superfine, fine and medium wool Merino ewes were fleece sampled between two to five years of age, there was a general trend for wool production to increase to a maximum at three years of age and then plateau, while wool quality traits tended to decrease with age, with variation in those trends related to bloodline (Hatcher et al. 2005). Similarly, when British long-wool sheep were culled at five years of age, the time to form a crimp and fibre curvature increased towards an asymptote, although wool bulk did not change with increasing age (Sumner & Dick 1997; Sumner & Upsdell 2001). On the other hand, fleece weight, staple length and fibre diameter attained a maximum at three years of age before decreasing, while fibre curvature and crimp frequency decreased curvilinearly with increasing age (Sumner & Dick 1997; Sumner & Upsdell 2001). The authors are unaware of any published reports of changes in wool characteristics of New Zealand feral or 'continuously farmed' sheep breeds, producing different wool types, living beyond five years of age while grazing in a common environment.

In the study reported here, objective wool measurement data were collected from three flocks of mixed-age New Zealand feral ewes that differed in fleece type and grazed together on the same property between 1990 and 2004. Individual sheep were culled when it was deemed from liveweight records, condition score and tooth condition that it was unlikely they would survive a further year, or when they had ceased to reproduce. The oldest ewe was culled at 12 years of age.

Methods

'Overarching' study

The wool samples measured in this experiment were derived from a larger study in which groups of sheep exposed to a feral existence of between 40 and 75 years, were captured from three different locations around New Zealand (Sumner et al. 2017). After capture, the flocks were managed in a common farming environment. It has become common practice in New Zealand to name flocks of feral sheep by the name of the location in which they lived. The flocks included in this study were the 'Hokonui', captured in the Hokonui Hills in central Southland, 43 km north-east of Invercargill (45°95′S,168°62′E); the 'Campbell Island', captured on Campbell Island situated in the Southern Ocean 590 km south of Bluff (52°33′S,169°09′E) and the 'Raglan', captured on the Paritata Peninsula in Raglan (Whaingaroa) Harbour 30 km west of Hamilton (37°46′S,174°36′E). Each feral flock had a different inherent fleece type and associated wool characteristics sufficient to consider it a distinct breed type (Sumner et al. 2017). Derivation of the Hokonui, is considered to be a Saxon Merino (fine-wool type), Campbell Island a Saxon Merino crossed with a British long-wool breed (known as a New Zealand Halfbred; mid-micron wool type) and Raglan a New Zealand Romney (coarse-wool type).

Details of the history of the three feral flocks in this study, along with their management and overall productivity following capture have been reported previously (Sumner et al. 2017). Briefly the three feral flocks grazed without human intervention for approximately 15 generations before being captured in 1976. Subsequently they were farmed according to normal farm management practices on several Ministry of Agriculture and Fisheries farms until 1990 when they were transferred to Whatawhata Research Centre. In 2000 they were transferred to Winchmore Research Station and finally dispersed in 2004. Some management protocols differed between the two properties.

Flock management in this study

At Whatawhata, the three feral flocks were grazed conjointly with approximately 1,500 experimental ewes of diverse breeds involved in several experiments. While at Winchmore the three feral flocks were combined and run separately from other flocks of experimental sheep. The live weight of all ewes was recorded after joining in April/May at Whatawhata and May/June at Winchmore. Lambs were individually identified at birth and their dam recorded.

Yearling ewes were shorn in September/October at both grazing locations, with the adult ewes being shorn in August (pre-lambing) at Whatawhata using a standard shearing comb (maximum thickness of 3 mm leaving a 2-4 mm stubble (Dabiri et al. 1995)). A 'winter' (or 'cover') shearing comb (maximum thickness of 7 mm leaving a 5 -7 mm stubble (Dabiri et al. 1995)) was used for the ewe shearing in August 2000 after the flocks were transferred to Winchmore. From 2001 onwards, the ewes at Winchmore were shorn in December to alleviate the risk of exposing them to late spring storms using a standard shearing comb. Individual greasy fleece weights were recorded at each shearing.

Sampling protocol

A sample of approximately 15 g of midside fleece was collected with a shearing handpiece using a standard comb, prior to shearing both the yearling and adult ewes. The sample was stored in a labelled plastic bag for later measurement. No wool samples were collected from adult ewes in 1991, 1992 or 1993. To reduce any potential bias due to a greater proportion of samples being measured from more young sheep than older sheep, only wool samples from ewes which supplied four or more wool samples were measured. This generated a total of 585 wool samples across the three feral flocks (Table 1).

The length of five wool staples from each sample were measured with a ruler and the mean calculated. The total number of crimps were counted along each of the five staples measured for staple length and the mean calculated. Mean fibre diameter, fibre diameter standard deviation between fibres, fibre diameter standard deviation along fibres and mean fibre curvature were measured using an OFDA2000 instrument, with a teased staple retained in a polyester slide (Sumner et al. 2009). Mean crimp frequency of each sample was calculated as the mean total number of crimps along each staple divided by the mean staple length. Estimated core bulk was calculated as Log_e core bulk = 1.06 + 0.61 Log_e mean fibre diameter – 0.42 Log_e mean fibre curvature + 0.11 (Log_e mean fibre curvature)^2 (Model 8 reported by Sumner et al. 2009).

To account for changes that occurred when the adult ewes were shorn with a 'winter' comb in 2000, and the different shearing policy at Winchmore when the ewes were shorn in December, greasy fleece weights, staple length and total number of crimps along the staple were adjusted to the amount of fleece grown in 365 days. This was achieved by proportionally adjusting the individual recorded measurement for the interval between the previous and 'current' shearing. Further adjustments were made using assumptions based on the seasonal pattern of wool growth (Bigham et al. 1978; Sumner et al. 1994). The time to form a crimp was calculated as 365 divided by the total number of crimps along the staple adjusted to the amount of fleece grown in 365 days.

Table 1 Number of measured wool samples from each flock by grazing location by age, collected from 24 Hokonui, 36 Campbell Island and 29 Raglan sheep.

Flock	Grazing	Age (years)												Number of
	location	1	2	3	4	5	6	7	8	9	10	11	12	samples
Hokonui	Whatawhata	21	19	18	15	16	12	10	6	0	0	0	0	117
	Winchmore	0	0	2	5	5	12	8	7	6	3	1	0	49
	Total	21	19	20	20	21	24	18	13	6	3	1	0	166
Campbell	Whatawhata	31	25	25	21	23	24	15	12	3	0	0	0	179
Island	Winchmore	0	0	2	6	9	12	12	4	4	2	1	1	53
	Total	31	25	27	27	32	36	27	16	7	2	1	1	232
Raglan	Whatawhata	26	22	23	17	18	18	13	2	1	1	0	0	141
	Winchmore	0	0	1	6	7	11	9	7	4	1	0	0	46
	Total	26	22	24	23	25	29	22	9	5	2	0	0	187
Grand total		78	66	71	70	78	89	67	38	18	7	2	1	585

Table 2 P value of the main effects for flock, age, grazing location and flock by age interaction. An estimate of the maximum and minimum standard error of the difference (SED) for age within flock for live weight and each of the measured wool characteristics is included. Bold text indicates significance at P<0.05.

Effect	Post-join live weight (kg)	Greasy fleece weight adjusted to 365 days (kg)	Staple length adjusted to 365 days (mm)	Mean fibre diameter (µm)	Fibre diameter variability between fibres (µm)	Fibre diameter variability along fibres (µm)	Mean fibre curvature (°/mm)	Crimp frequency (crimps/cm)	Time to form a crimp (days)	Estimated core bulk (cm^3/g)
Flock	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**
Age	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**0.02**	**<0.001**	0.22	**<0.001**	**<0.001**
Grazing location	0.30	**0.02**	0.17	0.11	**0.02**	**0.02**	**0.01**	**0.01**	**0.02**	0.08
Flock x age	0.56	**0.03**	**<0.001**	**0.02**	**0.003**	**0.002**	0.07	**0.04**	**<0.001**	0.48
SED maximum	4.1	0.4	12	1.7	0.6	0.8	8	0.6	3.3	1.6
SED minimum	0.7	0.1	2	0.3	0.1	0.1	1	0.1	0.6	0.3

Statistical analysis

A linear mixed model was fitted to the data using residual maximum likelihood (REML) in Genstat (VSN International 2019), with ewe and year of record as random effects and flock, grazing location, age, flock by age interaction, and the number of lambs weaned by the ewe, as fixed effects. Relocation of the flocks was not allowed for at the commencement of this study. As a consequence of relocation, the unbalanced number of sheep of each age at each grazing location rendered analysis of interactions involving grazing location meaningless.

Results

Sample number

The number of wool samples collected from each flock by grazing location by age, is shown in Table 1. A total of six Hokonui, 19 Campbell Island and 15 Raglan sheep provided all their samples while grazing at Whatawhata. No sheep provided all their samples while grazing at Winchmore.

Assessed effects

P values of the main effects for flock, age, grazing location and the flock by age interaction, for live weight after joining and each measured wool characteristic are shown in Table 2. The adjusted mean values for the interaction of flock by age for each measured wool characteristic are plotted in Figure 1.

Flock effect

There was a significant flock effect for live weight after joining and all of the measured wool characteristics. In the case of the three measured wool characteristics associated with fibre curvature, namely mean fibre curvature, crimp frequency and estimated core bulk, the between-flock rank was Hokonui highest, followed by Campbell Island and Raglan which was lowest. For all the other measured wool characteristics, except greasy fleece weight adjusted to 365 days wool growth, Raglan was higher than Campbell Island which was higher than Hokonui. In the case of live weight after joining and greasy fleece weight adjusted to 365 days wool growth, Raglan was heaviest, but Campbell Island and Hokonui were not significantly different (Figure 1).

Age effect

There was a significant age effect for all the measured characteristics except crimp frequency. Time to form a crimp, increased at a faster rate with ageing than mean fibre diameter. Live weight after joining increased to six years of age and then decreased, with greasy fleece weight adjusted to 365 days growth falling after two years of age. Mean fibre curvature, estimated core bulk and staple length adjusted to 365 days growth, all decreased linearly with increasing age.

Fibre diameter variability between and along fibres showed a similar trend with age, where the magnitude of the between-fibre variability was associated with the magnitude of mean fibre diameter. On the other hand, the magnitude of the along-fibre variability was less than between-fibre variability, reflecting the reduced rhythm of seasonal wool growth in the Merino compared with other coarse-wool breeds grazed at the same location (Sumner et al. 1994).

Grazing location effect

There was a significant grazing location effect for six of the measured wool characteristics. With relocation of the ewes from Whatawhata to Winchmore greasy fleece weight adjusted to 365 days wool growth, fibre diameter variability between and along fibres, and time to form a crimp increased, while mean fibre curvature and crimp frequency decreased (Table 3).

Flock-by-age effect

There was a significant interaction between flock and age for all the measured characteristics except live weight after joining, mean fibre curvature and estimated core bulk (Figure 1). The pronounced decrease in both greasy fleece weight and staple length adjusted to 365 days growth with increasing age, was more pronounced for the most productive Raglan breed, than for the least productive Hokonui breed, with the Campbell Island being intermediate. Crimp frequency and time to form a crimp,

Figure 1 Mean values for (a) live weight after joining (kg), (b) greasy fleece weight adjusted to 365 days growth (kg), (c) staple length adjusted to 365 days growth (mm), (d) mean fibre diameter (μm), (e) fibre diameter variability between fibres (μm), (f) fibre diameter variability along fibres (μm), (g) mean fibre curvature (°/mm), (h) crimp frequency (crimps/cm), (i) time to form a crimp (days) and (j) estimated core bulk (cm^3/g) within the Hokonui (▲), Campbell Island (■) and Raglan (●) flocks over time. Error bars shown are the minimum (on left) and maximum (on right) standard error of the difference (SED) for ewe age within each flock. Actual SED for a defined comparison is related to the number of measured samples in each age group within each flock (Table 1).

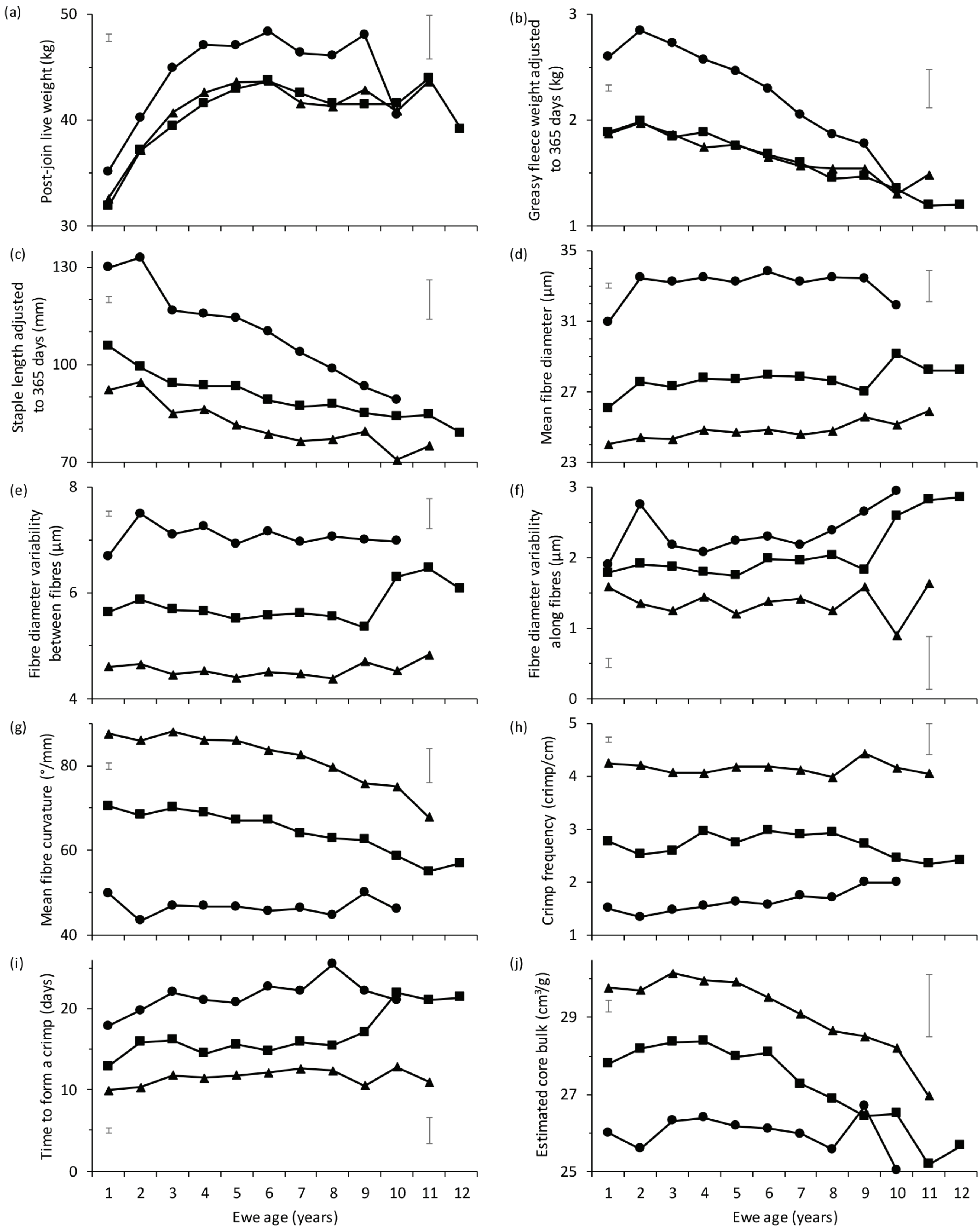

Table 3 Adjusted grazing location means and standard error of difference for live weight and each of the measured wool characteristics.

Effect	Post-join live weight (kg)	Greasy fleece weight adjusted to 365 days (kg)	Staple length adjusted to 365 days (mm)	Mean fibre diameter (µm)	Fibre diameter variability between fibres (µm)	Fibre diameter variability along fibres (µm)	Mean fibre curvature (°/mm)	Crimp frequency (crimps/cm)	Time to form a crimp (days)	Estimated core bulk (cm^3/g)
Whatawhata	40.6	1.7	90	28.2	5.5	1.6	66	3.0	16.2	27.6
Winchmore	43.4	1.9	96	29.0	6.2	2.4	61	2.6	17.8	27.0
Standard error of difference	2.6	0.1	5	0.5	0.3	0.3	2	0.1	0.6	0.3

exhibited a significant interaction between flock and age, where Hokonui sheep with the smallest crimp, exhibited a faster decline in crimp formation with increasing age compared to Raglan sheep with the largest crimp. Campbell Island sheep were intermediate in the rate of crimp development.

Discussion

Although there were statistically significant grazing location effects for six of the measured wool characteristics, the effects are of little practical relevance on account of their small magnitude and the disparity in numbers of ewes at the two grazing locations. These effects will not be further discussed.

In this study the live weight after joining of three flocks of feral sheep with different fleece types, showed a curvilinear relationship that increased to a plateau at five to six years of age before declining. As a comparison the live weight of Australian Merino ewes (Brown et al. 1966) and New Zealand Wiltshire and Perendale ewes (Sumner et al. 2012) began to decline a year earlier with the feral ewes having a lower mean live weight. Possible effects on live weight of sheep living in a feral environment have been discussed by Sumner et al. (2017). Despite the lower live weight of the feral ewes in this study relative to other continuously farmed breeds, the increasing live weight of the feral ewes during much of their lifetime is a clear demonstration that the sampled ewes were fit and healthy with no nutritional impediment to their productivity, particularly wool production.

While there are limited published data reporting age effects on live weight, there are fewer reports of age effects on objectively measured wool characteristics that can be compared with the data reported here, other than a single report for Australian Merino ewes (Brown et al. 1966) and a single report for New Zealand Perendale ewes (Sumner & Dick 1997).

In contrast to the published data the most striking result from this study was that while the ewes were still actively growing, greasy fleece weight declined linearly from two years of age. This is the first shearing after they have attained puberty. These results are in marked contrast to the Merino and Perendale ewes that attained a maximum greasy fleece weight at three to four years of age before declining (Brown et al. 1966; Sumner & Dick 1997).

Staple length in the current study declined linearly in a similar manner to greasy fleece weight from two years of age. In the Australian study, where staple length also declined in a linear fashion from two years of age, maximal greasy fleece weight was not attained until three to four years of age. In the case of the Perendale ewes staple length and greasy fleece weight also followed a similar relationship after achieving a maximal greasy fleece weight at three to four years of age.

Mean fibre diameter was another wool characteristic in this study that exhibited a different response to that observed in Australian Merino and New Zealand Perendale fleeces. In this study mean fibre diameter showed a slight progressive increase from two to eight years of age when the within group variability increased with few ewes remaining at older ages. In the Australian study mean fibre diameter of the Merino ewes increased to a maximum at about six years of age before it began to decline, while in the Perendale mean fibre diameter began declining after three years of age. Fibre diameter variability between fibres within the fleeces of the sheep in this study and the Perendale fleeces increased slowly over time. The authors are unaware of any studies that have reported age effects on fibre diameter variability along fibres within the fleece.

A number of measures of the crimp in staples and fibres have been reported. Crimp frequency in this study did not exhibit a significant age effect while the crimp frequency in Perendale ewes decreased slowly with age. The only characteristics measured in this study that did align well with data from the New Zealand Perendale were fibre curvature and core bulk. Fibre curvature progressively decreased as Hokonui and Campbell Island sheep aged. There was no defined effect for the Raglan sheep. This effect is visually apparent with older sheep having a larger and less clearly defined staple crimp. With the measurement of core bulk being derived by an algorithm involving fibre curvature (Sumner et al. 2009), core bulk of both groups of sheep decreased after two to three years of age as the fleeces exhibited progressively less springiness.

What might be the biological basis of the different age responses exhibited by the ewes in this study compared with those in the published reports?

Wool growth, as described by greasy fleece weight grown over a defined period of time, has previously been considered in Merinos to be derived from the following components (Turner 1956);

$$W = Y . S . R . A . F . N . \rho$$

where W is total clean wool weight per head, Y is percent clean yield, S is smooth body surface area, R is wrinkling factor, A is average fibre cross-sectional area, F is average fibre length, N is number of fibres per unit skin area, and ρ is the specific gravity of wool.

Of the characteristics considered by Turner (1956), approximations of W, S, A and F were measured in the current study with;

$$W' \propto S' . A' . F'$$

where W' was greasy fleece weight adjusted to 365 days growth, S' was smooth surface area of the skin estimated from live weight after joining, A' was mean fibre cross-sectional area estimated from mean fibre diameter and F' was mean fibre length estimated from staple length adjusted to 365 days growth.

Of the measured traits, staple length was the dominant characteristic in influencing greasy fleece weight with a correlation of $r = 0.68 \pm 0.02$ ($P<0.001$) explaining 46% of the variation in greasy fleece weight. The other characteristics are clearly of lesser importance as evidenced by the trends shown in Figure 1.

The authors are unaware of any published reports of the biological basis for a decline in wool follicle output as sheep age. It is of note that there was a similar proportional decline exhibited by each of the three flocks. This could be a reflection of a biological response that was present at the time the flocks became feral, before intensive selection for increased fleece weight was applied across the national sheep flock. Alternatively, it could be a survival response that developed during the period that the flocks were not subjected to human intervention to manage their welfare, as suggested by Sumner et al. (2017). The cause cannot be experimentally uncovered as anecdotally all continuously farmed flocks in New Zealand have been ‘modified’ by their owners during the last 100 years in an attempt to increase their inherent wool productivity. The marked lineal decline in wool growth from two years of age remains in all three feral flocks, which each grow a different wool type, after they have been intensively managed without the application of any selection pressure on wool production for several generations.

It is of note that in an earlier one-year study using a mixed-age sample of the feral flocks evaluated here, the older ewes exhibited a reduction in total wool follicle density and increased fibre seasonality associated with reduced follicle activity during winter compared to younger ewes relative to modern breed counterparts (Pearson et al. 1999).

The varied responses in terms of age effects recorded for the measured wool characteristics shown by these flocks, relative to Australian Merinos and New Zealand Perendales, highlight the complexity of the biological processes associated with wool growth and the expression of fibre crimp (Harland et al. 2018). In these feral flocks the time to form a crimp in the Raglan ewes is proportionately longer than in the Campbell Island and Hokonui flocks resulting in a significant flock by age effect ($P<0.001$). This aligns closely with the decline in staple length which also exhibited a significant flock by age effect ($P<0.001$). Clearly a different follicle regulation mechanism operates within these three feral flocks compared with the Australian Merino and New Zealand Perendale, which themselves differ slightly for some characteristics.

With the feral sheep demonstrating a different response while ageing to those reported for Australian Merino and New Zealand Perendale sheep, the trends reported here cannot be extrapolated to modern breeds beyond the normal age of culling. Further studies are required to understand the biological factors regulating cell division within the follicle that result in the different pattern of wool growth expressed by sheep that have lived in a feral environment for several generations, relative to ancestrally related sheep that have been farmed continuously.

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References

Bigham ML, Sumner RMW, Elliott KH 1978. Seasonal wool production of Romney, Coopworth, Perendale, Cheviot and Corriedale wethers. New Zealand Journal of Agricultural Research 21: 377-382.

Brown GH, Turner HN, Young SSY, Dolling CHS 1966. Vital statistics for an experimental flock of Merino sheep. III. Factors affecting wool and body characteristics including the effect of age and its possible interaction with method of selection. Australian Journal of Agricultural Research 17: 557-581.

Bruère AN, West DM 1993. Dental abnormalities. In: The sheep. Foundation for Continuing Education of the New Zealand Veterinary Association, Massey University, Palmerston North, New Zealand. Pp 197-220.

Dabiri N, Holmes CW, McCutcheon SN, Parker WJ, Morris ST 1995. Resistance to cold stress in sheep shorn by cover comb or standard comb. Animal Science 60: 451-456.

Harland DP, Vernon JA, Woods JL, Nagase S, Itou T, Koike K, Scobie DR, Grosvenor AJ, Dyer JM, Clerens S 2018. Intrinsic curvature in wool fibres is determined by the relative length of orthocortical and paracortical cells. Journal of Experimental Biology 221, jeb 172312. Doi 10.1242/jeb.172312.

Hatcher S, Atkins KD, Thornberry KJ 2005. Age changes in wool traits of Merino sheep in Western NSW. Proceedings of the Sixteenth Conference of the Association for the Advancement of Animal Breeding and Genetics 16: 314-317.

Pearson AJ, Ashby MG, Nixon AJ, Sumner RMW 1999. Seasonal wool growth patterns and the follicle and fibre characteristics of New Zealand feral sheep. Proceedings of the New Zealand Society of Animal Production 59: 34-38.

Sumner RMW, PB Baxter, MP Upsdell 2009. Prediction of core bulk using OFDA instruments. International Journal of Sheep and Wool Science 57: 10-24.

Sumner RMW, Bigham ML 1993. Biology of fibre growth and possible genetic and non-genetic means of influencing fibre growth in sheep and goats – a review. Livestock Production Science 33: 1-29.

Sumner RMW, Clarke JN, Pearson AJ, Speedy PM 1994. Repeatability of seasonal wool growth in Merino sheep. Proceedings of the New Zealand Society of Animal Production 54: 163-165.

Sumner RMW, Dick JL 1997. Changes in fibre and follicle characteristics related to wool bulk during the lifetime of Perendale ewes. Proceedings of the New Zealand Society of Animal Production 57: 65-69.

Sumner RMW, Scobie DR, O'Connell D, Henderson HV 2012. Relative performance of Wiltshire and Perendale sheep. Proceedings of the New Zealand Society of Animal Production 72: 28-34.

Sumner RMW, Scobie DR, O'Connell D, Henderson HV 2017. Relative live weight, fleece weight and reproductive rate of farmed feral sheep (*Ovis aries* L.). New Zealand Journal of Zoology 44: 319-341.

Sumner RMW, Upsdell MP 2001. Age effects and interrelationships between wool characteristics of genotypes used to develop GrowBulk sheep. Proceedings of the New Zealand Society of Animal Production 61: 100-103.

Turner HN 1956. Measurement as an aid to selection in breeding sheep for wool production. Animal Breeding Abstracts 24(2): 87-118.

VSN International 2019. Genstat for Windows 20th Edition. VSN International, Hemel Hempstead, UK. Web page: Genstat.co.uk